AN INTRODUCTION TO THE SCIENTIFIC STUDY OF THE SOIL

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PREFACE

This book is essentially a communication from a teacher to students, and is written because the science of the soil has developed so rapidly in recent years that the general agricultural student does not find it easy to procure a concise account of the subject.

Apart from those taking an Honours course and to whom this book can only serve as a preliminary survey, there are normally two principal groups of students whom the teacher of "Soil Chemistry" (as it is still called in this country), has to meet: agricultural *diploma* students whose studies are mainly vocational, and agricultural *degree* students whose work is essentially academic. I have endeavoured in this book to convey as concisely as possible what I regard as being practically essential to both groups of students, so that my future courses of lectures will be devoted to amplification, with an industrial bias to diploma students and with an academic bias to degree students.

While the book has been written essentially for the agricultural student of my own experience, I am not without hope that it may be of service to others—agriculturists, horticulturists, ecologists and so forth—who seek some general account of the present conceptions of the soil.

I can scarcely expect that every teacher of the subject will concur in all respects with the sequence and with the distribution of emphasis of this presentation. Very little is really known among us about the different methods of teaching this subject in our Universities and Colleges, and if this effort to put the gist of my

lecture course into book form provokes discussion and comment from other teachers it will perhaps serve a useful purpose to that extent.

I have avoided any detailed description of laboratory methods and made my sole object the presentation of a general conception of soil constitution and phenomena. Working details of analytical methods are given to students who pursue practical work in the laboratory, but such details are a source of pernicious weariness to the student who does not work in a laboratory.

While assuming the reader has some general knowledge of physical and chemical science (as well as of the elements of botany and geology) I have thought it advisable to offer in appendices, brief remarks (designed to create a working understanding) on Colloids, Surface Tension, and Hydrogen-ion Concentration.

The chapter on the Literature of the Science of the Soil is put last merely to preserve the sequence of the other chapters and not because it is most appropriately dealt with at the end of the lecture course. Indeed I think every serious agricultural student should have practice in the use of the literature during his course. For that reason I have not relegated this chapter to the second-class accommodation of an appendix.

My best thanks are due to my colleagues Mr. Geoffrey Milne, Mr. H. Trefor Jones, and Mr. J. S. Willcox, who kindly undertook the proof-reading and indexing; to Dr. J. A. Hanley for the majority of the mechanical analyses in Table 13 and for the comments thereon; and to the various publishers, editors and authors who have kindly consented to the quotation of experimental data and diagrams.

THE UNIVERSITY, LEEDS. N. M. COMBER.

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CHAPTER I

INTRODUCTION. THE SOIL AND THE PLANT

The plant normally lives and grows **in contact with** two media, the air and the soil.

The Plant and the Air

There are two chief processes involved in the contact of the plant with the atmosphere, (*a*) respiration, and (*b*) assimilation of carbon dioxide.

Respiration. This process which characterizes all living organisms is essentially an intake of oxygen and the oxidation or combustion of organic substances —chiefly carbohydrates and fats. During this oxidation which for carbohydrates may be represented in general terms by the following equation

$$C_xH_{2y}O_y + xO_2 \rightarrow xCO_2 + yH_2O$$

water and carbon dioxide are formed, the carbon dioxide being exhaled by the plant and energy being set free whereby the plant can live and grow. Respiration is continuous—day and night—during the whole life of the plant.

The Assimilation of Carbon Dioxide. The material stored up in the seed is only sufficient to provide substance for the growing parts and for respiration during the earliest days of development. Afterwards the plant must be in a position to manufacture the substances necessary for growth and respir-

ation. The first stage in this process is the absorption of carbon dioxide at certain parts of the surface of the green leaf, and the process cannot commence until the green leaf is formed. By a complicated series of reactions between this carbon dioxide and water taken up from the soil, carbohydrates are formed and some oxygen is set free. While the changes involved are still obscure, it seems certain that formaldehyde is an intermediate product and that this is polymerized to form hexoses, by the condensation of which more complex carbohydrates are formed. The following equations represent *in outline* the changes involved :—

(i) $CO_2 + H_2O \rightarrow CH_2O + O_2$
(ii) $6CH_2O \rightarrow C_6H_{12}O_6$.

This assimilation of carbon dioxide and formation of carbohydrates only takes place in daylight. The light waves at the red end of the spectrum are most effective. The process is essentially one in which the light energy becomes stored up in the organic substances. The process is dependent upon a number of conditions among which are the adequate supply of suitable potassium compounds and the presence of chlorophyll which is involved in the energy transformation. Being a synthetic process which is dependent upon light, it is commonly known as Photosynthesis.

By further changes some part of the carbohydrates formed by photosynthesis are converted into other compounds, notably proteins, and in some plants into fats also. The nitrogen, phosphorus and sulphur which are involved in the formation of proteins are normally obtained from the soil, although leguminous plants obtain some of their nitrogen from the air (p. 114).

The Plant and the Soil

From the soil a number of different substances are taken up by the plant. It is commonly said that nine of the elements so absorbed (Hydrogen, Oxygen, Nitrogen, Sulphur, Phosphorus, Potassium, Magnesium, Calcium and Iron) are essential to the plant, and the implication is made that other elements (e.g. silicon, sodium, manganese, etc.) which the plant takes up are absorbed because they happen to be there but play no essential part in the plant's nutrition. The statement that a certain limited number of elements are essential, and the implication that others are not, has arisen from experiments which appear to indicate that normal plants can be grown in water cultures when all the so-called "essential elements" but no others are present. It is important, however, to bear in mind two things in this connection.

(1) There is no precise and definite meaning attaching to the phrase "a normal plant." Plants may be regarded as "normal" while it is still possible for them to be bigger and more vigorous. For example, wheat plants may be grown in culture solutions containing the so-called essential elements and appear quite normal, but their growth is sometimes enhanced by the addition to the solution of colloidal silica. Moreover, the normality of the plant cannot be seen in the plant itself, for the essential function of a plant, as of all living things, is to reproduce its species, and while the absence of some particular soil element from a culture solution may not appear to have a detrimental influence upon the plant growing in it, there is little evidence as to what effect it may have upon the fertility of the succeeding generations.

(2) It must also be realized that there is no neces-

sary connection between the amount of any particular substance involved and its physiological effects. The most virulent poisons can produce their most serious results in extraordinarily small quantities, and extremely small quantities of some substances may have very important and far-reaching beneficial effects. The work of Mazé and others in recent years has given strong indications that a number of elements (e.g. iodine, fluorine, zinc) are essential to plant growth. One recent and impressive research in this connection is the demonstration by Miss Warington that a number of leguminous plants are incapable of normal growth in the absence of suitable boron compounds. Borax, when present in such small doses as 1 part in a million of the culture solution can supply the needs of these plants, but when the amounts are increased to 1 part in two or three thousand (still a very small proportion) the boron compound is actually harmful. There is no logical reason to suppose that other elements may not be beneficial for certain plants when present in one part in many millions, and be harmful when present in one part in a few millions. It is necessary, although somehow it seems rather difficult, for the student to realize that substances may exert important physiological effects when present in infinitesimally small and undetectable amounts.

Whatever elements may be necessary or dangerous to growing plants, in practice those people who grow plants in soil confine their attention to a very few, of which calcium, nitrogen, phosphorus and potassium are the chief. In other words, experience so far has shown that certain compounds of these four elements are the most likely things to affect the quantity and quality of crops. Hence it comes about that in the study of the soil, which in this country at any rate

has always been embarrassed by being pursued under the ægis of industrial agriculture, a great deal of attention has been given to the compounds of these four elements in the soil. The calcium compounds involved appear for the most part to affect the conditions of the soil (Chapter X), and it is generally supposed that any direct nutritional effect they may have upon the plant is of lesser consequence than their indirect effects. Of the other three outstanding elements, the nitrogen compounds (Chapter XI) stand in rather a different position from the compounds of phosphorus and potassium, and there are only a few general considerations common both to the nitrogen and also to the phosphorus and potassium compounds. Nitrogen compounds in the soil are intimately connected with the decomposition of organic matter and biochemical activities, and it has become usual to discriminate between the nitrogenous plant food and the "mineral" plant food.

Transpiration. During growth large quantities of water pass through the plant from the soil to the air into which it is evaporated. The water transpired varies but is usually about 300 times the weight of dry matter formed. (See Table 1.)

Limiting Factors in Plant Growth

Plant Growth. The period between the sowing of the seed and the reproduction of the next generation of seed may be roughly divided into three parts, the periods of germination, growth and maturation.

Germination. The relationship of the seed to the soil during germination is exclusively physical. A resting-place, a water supply, an air supply and a suitable temperature are the necessary conditions, and given these a seed can germinate anywhere. Water

enters the seed osmotically and internal pressures of the order of six or eight atmospheres are established. Respiration proceeds, thereby liberating energy for the movements of the growing plumule and radicle. Material stored in the seed is translocated to the growing parts, and this translocation involves considerable enzyme activity. Seeds normally contain carbohydrate, protein, various amino bodies, and sometimes fat. The enzyme *cytase* attacks the aleuron layer which encloses the "true" starch in starch grains, and *diastase* promotes the hydrolysis of starch and the consequent production of *maltose* and *dextrose.* Cane sugar is inverted under the influence of *invertase,* and *trypsins* bring about the breaking up of the proteins. In oil seeds *lipase* is responsible for a partial saponification of the oil and some part of the oil appears to be converted into carbohydrate. During germination there is a loss of weight of dry matter, for the formation of the new tissues of the plumule and radicle involves only material already present in the seeds, and the process of respiration involves the loss of some part of the stored material.

Growth. The closing of the germination period is marked by the development of root hairs in the radicle and the formation of chlorophyll in the plumule which emerges into daylight. The young plant is now in a position to take up materials from the soil and to assimilate carbon dioxide from the atmosphere, with the consequent formation of carbohydrates and other bodies required by the plant. The plant is absolutely dependent upon the formation of its chlorophyll-containing leaves by the time the materials stored in the seed for use during germination have been used up. When seeds are planted too deeply the stored material may become entirely exhausted before the green

leaves are formed above ground: the plant will then die. Translocation of the material formed in the leaf to the growing parts of the plant proceeds and is accompanied by the hydrolytic activities of the appropriate enzymes. The loss of material consequent upon respiration is negligible compared with the large increase initiated by the photosynthetic processes.

Maturation. The period of growth ultimately ceases and storage in the seed or in vegetative organs commences. During this period of maturation the gain in weight normally ceases and the loss occasioned by respiration becomes dominant. Translocation to the place of storage is normally preceded by enzyme hydrolysis and a subsequent rebuilding of the material to be stored.

Limiting Factors. During the development of the plant an enormous variety of chemical, physical and biological factors are involved. So far as quantities of material are concerned, the uptake of carbon dioxide and water and the subsequent formation of organic matter is outstanding. Reference to Table 1 will give a more precise conception of the obvious fact that the bulk of the dry matter of the plant is organic, and that the substances taken from the soil are relatively trivial in amount. Nevertheless these quantities of soil constituents have a controlling effect upon the formation of organic substances. Without small traces of iron, for example, and somewhat larger quantities of magnesium, chlorophyll cannot be formed. Without potash, photosynthesis cannot proceed, and without nitrogen, proteins cannot be formed.

Lying behind the uptake of these small but dominating amounts of soil substances, there is an amazing complication of physical, chemical and biological factors which determine their availability for the plant.

TABLE

THE APPROXIMATE COMPOSITION

All amounts are given

Crop and assumed Yield per Acre.	Proximate Composition.						Percentage Composition of Ash.								
	Water.	Oil.	Crude Protein.	Sol. Carbohydrate.	Crude Fibre.	Ash.	P_2O_5.	K_2O.	CaO.	MgO.	Na_2O.	Fe_2O_3.	SO_3.	Cl.	SiO_2.
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
WHEAT: Grain 32 bushels	13·0	2·0	12·0	69·0	2·0	2·0	50·0	33·0	3·0	10·0	0·2	1·0	2·0	0·2	1·0
Straw 30 cwt.	14·0	1·25	2·0	40·0	36·0	6·75	3·0	15·0	4·5	1·5	0·1	1·0	4·0	1·5	65·0
BARLEY: Grain 40 bushels	15·0	2·0	9·0	68·0	5·0	1·0	35·0	30·0	3·0	7·5	1·5	0·5	2·0	1·5	20·0
Straw 25 cwt.	14·0	1·75	3·25	42·0	34·0	5·0	3·0	20·0	10·0	2·0	6·0	1·0	5·5	7·0	45·0
TURNIPS (Roots) 15 tons . .	91·0	0·25	1·0	6·0	1·0	0·75	10·0	50·0	12·0	2·5	8·5	0·5	12·5	5·0	1·0
MANGOLDS (Roots) 25 tons .	88·0	0·1	1·0	9·0	1·0	0·90	10·0	50·0	4·5	3·0	20·0	0·5	3·0	4·0	2·5
POTATOES (Tubers), 6 tons	76·0	0·1	2·0	20·0	1·0	0·90	17·0	60·0	2·5	5·0	2·5	1·0	6·5	3·0	2·0
MEADOW HAY, 1½ tons . .	14·0	2·5	9·0	41·5	26·0	7·0	6·0	25·0	15·0	7·0	5·0	1·0	7·5	7·5	30·0

I

OF SOME COMMON CROPS

in Round Numbers.

N lb. per Acre.	Removals from Soil by Average Crop. Ash Constituents, Lb. per Acre. P_2O_5 lb.	K_2O lb.	CaO lb.	MgO lb.	Na_2O lb.	Fe_2O_3 lb.	SO_3 lb.	Cl lb.	SiO_2 lb.	Water Transpired in average Season. Tons per Acre.	Removal from Air by Average Whole Crop. CO_2. Tons per Acre.
60	20	30	10	7	3	2½	20	2½	100	600	3
50	20	35	10	7	5	1½	18	5	70	550	2¾
50	25	125	30	7½	20	1½	30	12½	2½	400	2½
85	50	250	25	15	100	2½	15	20	7½	900	5
45	25	80	3	7	3	1½	8½	4	3	450	2
50	12	50	30	15	10	2	15	15	60	375	2

Moreover, the plant itself is very dependent upon the physical conditions of the soil—water supply, air supply, temperature, a sufficient cohesion to give anchorage to the plant and yet sufficient incoherence to give facilities for the movement of the shoot and the root.

It is a simple but fundamental and important consideration that for maximum fertility *all* the necessary conditions and provisions for the growth of plants must obtain. In agricultural practice it often happens that infertility and crop failure arise through the combined efforts of *several* defects or deficiencies, and in the industry of farming a good deal of money has been wasted in efforts to rectify one condition or to supply one deficiency without attention to the others. Many of the Rothamsted plots illustrate the possibility of this sort of thing. The unmanured plots are deficient in both mineral and nitrogenous foods; the application of minerals alone gives a small response; the application of nitrogenous fertilizers alone gives a somewhat bigger response so far as bulk is concerned (although disproportionately high quantities of nitrogen frequently involve the existence of disease); the application of *both* mineral and nitrogenous fertilizers gives a response which is far in excess of the sum of the responses due to minerals alone and nitrogen alone.

It must also be noted that there is a limit to which any one factor involved in plant growth may be increased without detriment to some other factor. The simple consideration of the relationship of air supply, water supply and temperature will make this clear. The more the water supply is increased the less are the facilities for aeration, and the lower is the temperature of the soil. These three factors are all

interdependent, and the improvement of any one of them involves the suppression of one of the others.

For most practical purposes the limiting factors which determine a state of infertility are to be found in the soil conditions, but when soil conditions are at their best the carbon dioxide supply in the air remains a limiting factor. Recent work in Germany has shown that increasing the carbon dioxide content of the air up to a certain point results in enhanced growth. This consideration may become important in glasshouse work, but it is hardly likely to have practical possibilities in the field. The carbon dioxide produced by decomposing organic matter has been suggested as a possible source for this purpose.

Pedology. It was at one time supposed that the scientific study of the soil was mainly a matter for chemists and that the chemistry involved was fairly simple and straightforward. The following chapters will show that the chemistry of soils is far from being simple and straightforward and that in spite of the big advances made during the last fifteen years or so, a great deal of the fundamental chemistry of the soil is still obscure. Indeed it is quite likely that the state of our knowledge of general chemistry is a limiting factor to the development of soil chemistry. Almost every new development in physical chemistry seems to throw fresh light upon soil problems.

As men of science gave more attention to the soil not only did it become apparent that the higher ramifications of physical, colloid and organic chemistry are involved, but also that microbiology and physics are involved along with chemistry in the study of soil fertility.

It was not unnatural, therefore, that the segregation of the science of the soil as a special subject so to

speak with a name of its own, was suggested in various quarters. The suggestions first put forward did not receive a very warm welcome and were, in fact, opposed by some students of the soil in this country. Such opposition was quite sound, for the application of a particular science or several sciences to an industrial problem does not necessarily constitute a new subject. Nothing can really attain the dignity of a " subject " as the word is understood in scholastic curricula, until it has something fundamental which it can call its own. The mere application of chemistry and physics to minerals and rocks does not make geology, and the application of those sciences to the soil does not make a new subject.

In recent years, however, the outlook has been considerably changed by the outstanding work of the Russian School. It may fairly be claimed that the study of soil formation processes and soil types which is briefly discussed in Chapters IV and XIII, has given to Soil Science a fundamental characteristic which has been properly recognized by the adoption of the word Pedology [1] to describe the science of the soil. The work of Sibirtzev, Glinka, Stebutt and others has put a backbone into the study of soils and turned that study into Pedology, in the same way that William Smith put the backbone into the study of rocks and made it Geology.

The word Pedology has been almost unanimously accepted on the Continent and to a large extent in America. In this country there are several eminent pedologists who are still reluctant to admit that description of themselves. They will, however, agree that in view of its now frequent use the student must be informed what the word means and whence it came.

[1] Gr. πέδον = soil.

CHAPTER II

SOIL GENETICS: THE MINERAL MATTER

The Parent Material. The rocks of the earth's surface are the manifest parent material of the mineral matter of soil.

The Original or Igneous Rocks. These rocks contain many crystalline minerals among which the Felspars, Micas, Hornblende, Augite, Olivine, Quartz and Apatite make a sufficiently representative list for present purposes.

The Felspars have the "ideal" formula $R_2O.Al_2O_3.6SiO_2$, or $R_2Al_2Si_6O_{16}$, where R is generally Na, K, or Ca. The potash felspar is known as *orthoclase* and the others as the *plagioclase* felspars. The plagioclase felspars include among others *oligoclase* (a sodium-calcium felspar) and *albite* (a sodium felspar). The felspars are white, grey or sometimes slightly pink crystalline minerals.

Micas are complex aluminium-containing silicates of sodium, potassium and sometimes magnesium, and often contain some iron. They also contain some hydrogen. Those containing much iron and which are therefore dark coloured are known as *biotite*; the white or slightly coloured micas are called *muscovite*. The formula $K_2O.3Al_2O_3.2H_2O.6SiO_2$ or $K_2Al_6H_4Si_6O_{24}$ is the basal formula of muscovite.

Hornblende is a silicate containing magnesium, calcium, aluminium and some iron.

Augite has almost the same chemical composition as hornblende, differing chiefly in certain physical properties.

Olivine is a silicate of magnesium and iron and under the influence of water and carbon dioxide gives rise to serpentine—a magnesium silicate.

Quartz is a crystalline form of silica and is a constituent mineral of most original rocks.

Apatite is a crystalline form of a calcium phosphate, and *fluor-apatite* a double phosphate and fluoride of calcium, $3Ca_3(PO_4)_2.CaF_2$. Such minerals are presumably the source of natural soil phosphorus compounds.

The Metamorphic and Secondary Rocks. The general facts about the formation of these " derived " rocks is a familiar—or if not, an easily accessible—story. The metamorphic rocks contain, in addition to the original minerals, others formed from them, such as Sillimanite, Andelusite, etc., but there is little general difference so far as soil formation is concerned between these and the original minerals.

The secondary sedimentary rocks are of great importance. They include the chalks and limestones which contribute large amounts of calcium carbonate to the soil, and those sands and clays in which particles of different sizes and compositions, formed from different minerals of the same rock, have become widely separated.

Both original and secondary rocks have in some areas become covered by material transported by ice and deposited when the ice melted or by the water running from the moraine. This *glacial drift* covers a large area of this country north of the Thames. It

is in some places composed of material brought a long distance and having no relation to the rock below, in others the material has been transported only a short distance and deposited on rock similar to that whence it came.

The same minerals, in worn fragments, together with some of their decomposition products such as hydrated oxide of iron in the form of *limonite*, make up the secondary rocks. But the separation of the larger particles of quartz for example, from the smaller particles of the silicates—original and derived—brings about large alterations in the ratio of the various chemical constituents. Significant differences in the composition and properties of soils may arise from these differences in the parent material (p. 54).

The Mineral Silicates. The silicates are the most prominent of the rock-forming minerals. There are many obscurities about their chemistry, because their sparing solubility, their high melting point, and their manifest complexity make the study of them difficult.

The alliance of silicon and carbon which is indicated in the periodic classification of elements has suggested that the multiplicity of silicates may be explained on the same lines as the large and indefinite number of carbon compounds. Starting with the formula of orthosilicic acid, $Si(OH)_4$, the formulæ of a large number of hypothetical acids can easily be constructed. Orthodisilicic acid, $H_6Si_2O_7$, for example, follows from the union of two molecules of $Si(OH)_4$ and the elimination of the elements of a molecule of water. Starting with metasilicic acid H_2SiO_3, there follow in a similar way metadisilicic acid $H_2Si_2O_5$, metatrisilicic acid $H_4Si_3O_8$ etc. Almost all the natural silicates may be regarded as salts of these hypothetical silicic acids, for example :—

Salts of orthosilicic acid	. .	H_4SiO_4
Olivine	. . . .	Mg_2SiO_4
Muscovite	. . .	$KAl_3H_2(SiO_4)_3$
Salts of orthodisilicic acid	. .	$H_6Si_2O_7$
Barysilite	. . .	$Pb_3Si_2O_7$
Salts of orthotrisilicic acid	. .	$H_8Si_3O_{10}$
Akermanite	. . .	$Ca_4Si_3O_{10}$
Salts of metasilicic acid	. .	H_2SiO_3
Enstatite	. . .	$MgSiO_3$
Tremolite	. . .	$CaMg_3(SiO_3)_4$
Salts of metadisilicic acid	. .	$H_2Si_2O_5$
Petalite	. . . .	$LiAl(Si_2O_5)_2$
Salts of metatrisilicic acid	. .	$H_4Si_3O_8$
Orthoclase	. . .	$KAlSi_3O_8$
Albite	. . . .	$NaAlSi_3O_8$

Silicates containing aluminium. Very many natural silicates contain aluminium and from the viewpoint of soil chemistry these are very important. According to older views the alumina in these compounds functions as a base, orthoclase felspar being regarded as a double silicate of potassium and aluminium. Alumina, however, is amphoteric; it functions as a base in the presence of strong acids forming aluminium salts, and as an acid in the presence of strong bases, forming aluminates. In the presence of silicic acid—a very weak acid—and potash and other strong bases, it is most likely that alumina behaves as an acid and that orthoclase felspar, for example, will not be a *potassium aluminium silicate,* but a *potassium aluminosilicate.* This is the prevalent view of the constitution of these silicates and is mainly due to Vernadsky, who has been able to account for all the aluminium silicates by postulating five groups of aluminosilicic acids whose empirical formulæ are :—

1. Aluminosilicic acid .	$H_2O.Al_2O_3.SiO_2$	or $H_2Al_2SiO_6$
2. Aluminodisilicic acids	$H_2O.Al_2O_3.2SiO_2$	or $H_2Al_2Si_2O_8$
	$2H_2O.Al_2O_3.2SiO_2$	or $H_4Al_2Si_2O_9$
	$3H_2O.Al_2O_3.2SiO_2$	or $H_6Al_2Si_2O_{10}$
3. Aluminotrisilicic acids	$H_2O.Al_2O_3.3SiO_2$	or $H_2Al_2Si_3O_{10}$
	$3H_2O.Al_2O_3.3SiO_2$	or $H_6Al_2Si_3O_{12}$
4. Aluminotetrasilicic acids	$H_2O.Al_2O_3.4SiO_2$	or $H_2Al_2Si_4O_{12}$
5. Aluminohexasilicic acid	$H_2O.Al_2O_3.6SiO_2$	or $H_2Al_2Si_6O_{16}$
	$3H_2O.Al_2O_3.6SiO_2$	or $H_6Al_2Si_6O_{18}$
	$9H_2O.Al_2O_3.6SiO_2$	or $H_{18}Al_2Si_6O_{24}$

Regarding the soil forming minerals as a whole, there are three outstanding groups of constituents which are of fundamental importance in soil chemistry, namely :—

1. **Strong Bases.** Lime, magnesia, soda and potash are predominant.

2. **Sesquioxides,** i.e. oxides of iron and aluminium.

3. **Silica.**

The Decomposition of Mineral Silicates. Weathering. The mechanical disintegration of original rocks consequent upon changes of temperature and the unequal expansion and contraction of the constituent minerals, the freezing and expansion of water in crevices and so forth, is a familiar story. Accompanying this mechanical disintegration there is a variety of chemical changes. Locally in the neighbourhood of hot springs and in volcanic regions, the effect of steam and other hot gases, whose action is generally termed *pneumatolysis*, accounts for the rapid weathering of some lavas. *Oxidation* of some rock constituents is important. Ferrous iron is oxidized during the weathering of rocks, giving rise to yellow, red or brown fragments from such dark coloured rocks as basalts and certain clays. Oxidation involves an increase of volume and thereby acts as an agent of mechanical disruption.

The most important part of the decomposition of

minerals is attributed to the action of water. *Hydration* is universally common and is the usual accompaniment of oxidation, but *solution* of minerals and their constituents by natural waters is probably of greatest importance.

The action of water and of solutions on minerals has been very extensively studied and the salient facts are :—

(1) Water in contact with nearly all minerals brings some of the constituents of the minerals into solution.

(2) This action is not generally and solely a true solvent action *on the mineral.* Hydrolysis and decomposition of the mineral take place. The solutions are usually alkaline and they do not contain the constituents of the minerals in the same proportions that obtain in the minerals themselves. Analysis of the solutions shows that there is a preferential removal of the strong bases.

(3) The action of water on minerals is greatly accelerated by the presence of carbon dioxide in the water.

(4) The action of water on minerals appears to go on continuously, provided that the products of solution are continuously removed.

It is impossible to be very precise about the chemical action of water on mineral silicates, but the familiar action of water on orthoclase felspar may be considered as typical of what takes place. Orthoclase may be regarded as the potassium salt of one of the aluminohexasilicic acids, $K_2Al_2Si_6O_{16}$ ($K_2O.Al_2O_3.6SiO_2$) and with water will undergo hydrolysis thus :—

$$K_2Al_2Si_6O_{16} + 2H_2O \rightarrow 2KOH + H_2Al_2Si_6O_{16}.$$

The aluminohexasilicic acid formed by this hydrolysis undergoes further change thus :—

$$H_2Al_2Si_6O_{16} + H_2O \rightarrow H_4Al_2Si_2O_9 + 4SiO_2.$$

TABLE 2

ANALYSES OF FRESH AND DECOMPOSED DIORITE (Merrill)

	1	2	3	4	5	6
Constituent.	Fresh Diorite.	Decomposed *Diorite.*	Decomposed Rock. Percentage of original Rock on assumption of no loss of Al_2O_3.	Calculated loss for Entire Rock.	Percentage of each Constituent *saved.*	Percentage of each Constituent *lost.*
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
SiO_2 . .	46·75	42·44	29·32	17·43	62·69	37·31
Al_2O_3 . .	17·61	25·51	17·61	0·00	100·00	0·00
Fe_2O_3 . .	16·79	19·20	13·26	3·53	78·97	21·03
CaO . .	9·46	0·37	0·26	9·20	2·70	97·30
MgO . .	5·12	0·21	0·15	4·97	2·83	97·17
K_2O . .	0·55	0·49	0·34	0·21	61·25	38·75
Na_2O . .	2·56	0·56	0·39	2·17	15·13	84·87
P_2O_5 . .	0·25	0·29	0·20	0·05	80·11	19·89
Ignition . .	0·92	10·92	—	0·00	100·00	0·00
Net loss of original material .	—	—	38·47	—	—	—
	100·01	99·99	100·00	37·56	—	—

Silica separates and an aluminodisilicic acid $H_4Al_2Si_2O_9$ or $2H_2O.Al_2O_3.2SiO_2$ remains. This acid is *kaolin*, and its purest form is china clay.

This main line of action may be accompanied by subsidiary reactions such as a reaction between the potassium hydroxide (or the potassium carbonate which it will obviously form) and the kaolin, with the formation of other bodies. Also the silica may be partially removed by the alkaline solution.

The outstanding facts are that *the strong bases tend*

to be split off, some silica is also liable to be split off, and the sesquioxides are the most obdurate constituents of the mineral.

These same general facts are indicated by a study of the differences between the composition of fresh and disintegrating rock. This has been extensively studied in America by Merrill, who made complete analyses of the fresh unweathered rock, and of the weathered material immediately overlying it. The analyses of the fresh and decomposed rock cannot be compared directly since it is impossible to ascertain what weight of original rock any given weight of the weathered product was formed from. For the purposes of an accurate comparison it would be necessary to express both sets of results as percentages of the original rock. For example, in column 2 of Table 2, which is quoted from Merrill's results, the percentage of alumina in the weathered rock is higher than in the original rock. This is because the percentage loss of material from the rock as a whole is greater than the percentage loss of alumina. There is no accurate means of finding

TABLE 3

CONSTITUENTS LOST FROM FOUR DIFFERENT ROCKS (Merrill)

The figures are percentages of the original amount of the constituent present

	Granite	Gneiss.	Syenite.	Basalt.
SiO_2 . .	14·89	52·45	62·18	65·56
Al_2O_3 . .	3·23	0·00	0·00	0·00
Fe_2O_3 . .	0·00	14·35	86·17	88·84
CaO . .	25·21	100·00	87·90	47·24
MgO . .	1·49	74·70	82·10	96·38
K_2O . .	31·98	83·52	81·85	83·34
Na_2O . .	28·62	95·03	97·11	74·41

what weight of fresh rock has given rise to a given weight of weathered rock; as the nearest means of estimating it Merrill assumes that there has been no loss of alumina. On this basis the analysis of the weathered rock is recalculated and the percentages obtained as percentages of the original rock. In column 4 the amounts of material lost are expressed as percentages of the original rock. In column 6 they are expressed as percentages of the original amounts of the respective constituents. From column 6 it will be seen that *the greatest relative loss falls on the bases lime and magnesia, potash and soda, the loss of silica is considerable, and the loss of oxides of iron and aluminium is least.* This result is quite general and is further illustrated by the data in Table 3.

The student must carefully discriminate between the separation of a constituent *from its original compound* and its separation from or deposition in *the soil.* For example, it does not follow that because the bases are most easily split off *from the silicates* that they are necessarily easily leached *from the soil.* Under arid conditions they are not. (See Chapter IV.)

CHAPTER III

SOIL GENETICS: THE ORGANIC MATTER

Organic matter is an essential and characteristic constituent of soils. The bulk of it is derived from plant residues which decay in the soil, and from dressings of dung, etc.

The Oxidation of Soil Organic Matter. Organic matter is oxidized in the soil under the influence of various micro-organisms which derive their energy from the process. Oxygen is taken up and carbon dioxide is formed (p. 82). The amount of oxygen taken up or the amount of carbon dioxide formed may be estimated and taken as a measure of the micro-organic activity. Now the micro-organic activity of soils is intimately associated with fertility (p. 111) and the amounts of oxygen absorbed and of carbon dioxide liberated may therefore give some index of fertility on soils of the same type which are similarly situated. In one series of such soils it has been shown by Russell that the order of the amounts of oxygen taken up in a given time under fixed conditions is also the order of productiveness.

Russell computes that the amount of oxygen absorbed by the farmyard manure plot in Broadbalk Field is of the order of 2 litres per square metre per day. Average arable land will probably absorb somewhat less than this.

Not much is known of the many changes whose sequence comprises this decomposition of proteins, carbohydrates and other organic constituents of plants, but two main types of the decomposition are recognized and these may conveniently be labelled the *direct* decomposition and the *indirect* decomposition.

The Direct Decomposition of Soil Organic Matter. The decomposition of some part of the non-nitrogenous constituents and of a large part of the protein proceeds steadily and "normally" to the formation of carbon dioxide, water, ammonia and such simple and "final" products of organic disintegration, and involves the intermediate production of organic acids. Its economic functions are the maintenance of the important bacterial life of the soil and the production of nitrate (p. 111).

The Indirect Decomposition of Soil Organic Matter. A small part of the protein and a larger part of the carbohydrate decompose to the stage of producing a very complex brown or black colloidal material known as *humus.* This material undoubtedly undergoes further oxidation but only slowly. Under normal conditions its oxidation does not exceed its formation and it is regarded as a permanent constituent of the soil.

Products which strongly resemble humus are formed by the condensation of amino-acids and sugars. Since certain amino-acids and sugars are undoubtedly formed during the decomposition of organic matter in the soil, the formation of humus may be due in part to such condensations. Another possibility is the formation of humus by the absorption of oxygen by lignin. The walls of young cells are composed of cellulose, but as a cell grows, a lignocellulose is produced—the amount of which varies from 20-30 per cent. in many plants to 50 per cent. in trees. This lignin material

can under certain conditions absorb oxygen with the formation of a material very like soil humus. This is attracting much attention as one of the possible processes of humus formation in soils. It has been pointed out, however, that sphagnum which contains practically no lignin, is a prolific source of humus.

Humus. This word is unfortunately used in more than one sense. It is sometimes used to describe the whole of the organic matter of the soil. Its use in this sense, however, is more popular than scientific ; it is not common in the literature of soil chemistry and may be disregarded here. Even among soil chemists, however, the word has two uses. It is used as the name of the *whole* of the dark colloidal complex of very slowly oxidizable organic matter, and it is also used as the name of a *specific fraction* of that complex as will shortly be described. In this book the convention will be adopted of writing " humus " for the whole of this colloidal organic complex which is partially arrested in its oxidation, and " humus fraction " for the specific fraction mentioned above.

The Fractionation of Humus. By extraction with alkali humus may be divided into two parts, one remaining insoluble in the alkali and called *humin,* and another soluble in the alkali. If the alkali solution is treated with excess of acid, one part of the dissolved organic matter remains in solution ; this is sometimes called *fulvic acid.* Another part is precipitated as a dark brown voluminous precipitate ; this is the *humus fraction.* The humus fraction may be further subdivided into *hymatomelanic acid* which dissolves in alcohol, and *humic acid* which is insoluble in alcohol.

A further fractionation of the humic acid can be made by extraction with pyridine, in which one part is soluble and the other insoluble.

This fractionation may be summarized thus :—

- **Humus**
  - *Insol. in alkali* — Humin
  - *Sol. in alk.*
    - *Pptd. by acid* — Humus fraction
      - *Sol. in alcohol* — Hymatomelanic acid
      - *Insol. in alc.* — Humic acid
        - *Sol. in Pyridine.*
        - *Insol. in Pyridine.*
    - *Not pptd. by acid* — Fulvic acid

Very little is known about the chemical composition of these fractions or of their relation to one another. The various alkali-soluble fractions are thought to be the products of certain stages in the breakdown of humin. Each fraction is undoubtedly a complex of many substances and the student must not be misled by the individualistic and unfortunate names—such as humic acid—to suppose that any one of the fractions is to be regarded as a single chemical compound.

The humus fraction which is the most easily isolated has been studied more than any other. A brief account of its main chemical and physical properties will follow, but it must be understood that although it is possible to say more about the humus fraction than about any of the other fractions of the colloidal organic matter, the humus fraction does not necessarily make a more important contribution to the fertility of the soil than the so-called fulvic acid or the humin.

The humus fraction varies in its ultimate composition, but analyses of the fraction obtained from various soils are all of the same order. Round figures approximating to the average composition are

$$C = 50\%,\ O = 35\%,\ N = 5\%,\ H = 5\%,\ \text{Ash} = 5\%.$$

The humic acid portion of the humus fraction, and its salts of calcium and other polyvalent metals, are colloidal gels. The salts of potassium, sodium and ammonium, however, are true electrolytes and from a study of their solutions Odén has shown that humic acid is a true acid, or more probably a mixture of true acids.

The humus fraction has a strong absorptive power for bases. It contracts enormously on drying, and if the drying is not excessive and prolonged the dried gel can imbibe water again with much swelling.

The humus fraction belongs to the so-called "emulsoid" group of colloids. It is not much affected by small concentrations of electrolytes. It "protects" the mineral particles. China clay, for example, which has been artificially protected with it will remain much longer in suspension and be less affected by neutral salts than the unprotected clay.

The Functions of Organic Matter in the Soil. Undecomposed organic matter incorporated with the soil produces in a quite obvious way, an opening of the soil. This effect may persist for a time after the organic matter has decomposed. In heavy soils this opening action is usually wholly desirable, but in sandy soils which are already loose and open it is generally harmful. This is one reason for the general desirability of spring applications of short manure to light land and earlier applications of long manure to heavy land.

The Biological Importance of Organic Matter. Soil Organisms. Soil organic matter provides food and energy for the vast miscellany of micro-organisms. The diversity of these organisms is engaging much attention, particularly at Rothamsted, where a large amount of work has already been done. The investi-

gations, however, are beset with enormous difficulties, and a large part of the work hitherto has been devoted to the study of a suitable development of technique. The soil contains *Algæ* and the Rothamsted workers show that in addition to those which, developing on the surface, contain chlorophyll and derive their energy from light, there are others beneath the surface in which the chlorophyll is presumably inoperative and which derive their energy from the soil organic matter. A vast number of species of *Fungi* have long been known to exist in soil; little is known about their relationships to crop-producing power. Some of them are symbiotic with trees and plants (mycorhiza) and some are probably parasitic. The slime fungus *Plasmodiophora Brassicæ* is responsible for "Finger and Toe" in cruciferous crops. *Actinomyces* occur and, so far as present knowledge goes, they are chiefly of economic importance in connection with the incidence of common scab on potatoes. Soil *Protozoa* are of importance in so far as they appear to feed upon bacteria and their destruction by sterilizing agents has important results (p. 117). The *Bacterial Flora* of the soil is prolific. Although only comparative methods of counting are yet reliable, there are evidently many millions of bacteria in each gram of normal surface soil. Many bacteria are probably involved in the indispensable process of humification, and other important bacteria are *Clostridium Pasteurianum*, *Azotobacter chroococcum*, *Bacillus Radicicola*, *Nitrosamonas* and *Nitrobacter*. The part played by these in soil phenomena is dealt with in Chapter XI.

The Physical Effects of Humus. Humus has marked effects on the physical properties of soil. Its effects are usually equally desirable on heavy and on light land. It binds a sandy soil and lightens a heavy soil.

This apparent contradiction is easily understood from the following considerations.

The chief physical defects of a clay soil are a too close and coherent texture and inadequate drainage. These defective conditions are commonly improved by the addition of lime. It will be explained later (p. 61) that this action of lime is due to the precipitate it forms with the hydrophilous water-imbibing colloidal matter coating the surfaces of the particles. This precipitate entrains the particles and loosely cements them together. Now humus is, in normal soils, a constituent of the hydrophilous coating of the particles, and in conjunction with lime it facilitates the flocculation or aggregation of the clay particles. The beneficial effect of humus on the texture of heavy soils is therefore dependent upon the presence of lime or some agency whereby humus is kept in the coagulated or gel form. In the absence of sufficient lime, the humus alone may even have an opposite effect upon the clay of soils, protecting and deflocculating it, and causing it to be washed downwards in the drainage water.

The chief physical defects of a sandy soil are a looseness and incoherence of the particles and an inadequate water-holding power. The binding power of coagulated humus operating in such soils will reduce the loose condition of the particles, giving body to the soil and providing better seed-bed conditions. The binding of the particles may increase rather than decrease the drainage channels through the soil, but nevertheless the coating of the soil aggregates, and the lining of the drainage channels with water-imbibing colloidal matter, increases the water-holding power of the soil.

Both extremes of texture in a mineral soil are

therefore improved by humus, and the moisture and temperature conditions are modified accordingly.

The Chemical Effects of Humus. Before it became generally acknowledged that the main source of carbon for plants is the carbon dioxide of the air, it was supposed that the plant absorbed organic matter from the soil. Humus, in fact, was regarded as a principal plant food and as the source of carbon for the plant. This supposition was almost entirely abandoned after de Saussure had shown that the carbon of plants is derived from the air, and Liebig had convinced the plant physiologists of the truth of de Saussure's conclusions. Recent experiments have shown, however, that humus *can* be used as a source of nitrogen for plants, although it is impossible to say that humus functions in normal soils as a direct source of nitrogen, or that the nitrogen is assimilated without previous decomposition of the humus.

The power of humus to absorb bases and hold them against the leaching action of water is one of its important functions in the soil (p. 90).

Humus—or some part of it—behaves as a weak acid, and with the humates it has an important regulating or " buffer " action on the hydrogen-ion concentration of the soil.

The Degree of Humification. The knowledge of the total amount of organic matter in a soil is of limited value. Its effective decomposition and the proportion of it which exists as humus are more important than the total amount of combustible matter. Robinson has made the suggestion that it may be possible to discriminate between the humified and the non-humified organic matter by treating the soil with hydrogen peroxide which it is thought will attack only the humified matter. Robinson's investigations on

these lines indicate that in the majority of fertile soils and also in peats, about 80 per cent. of the organic matter is humified, while in other soils the figure may fall as low as 40 per cent.

The Isolation of Individual Organic Compounds. In addition to the general fractionation of the humus, Schreiner and Shorey, and some other workers, have isolated a number of specific organic compounds from soils. Some of these may be common constituents of the majority of soils. Others are certainly more characteristic of the particular soils examined. The compounds isolated include a number of organic acids, glycerides, carbohydrates and amino-compounds. It is difficult to say what significance is attached to these compounds, although one or two have been shown to have a definite effect upon the plant. Thus dihydroxystearic acid is toxic while vanillin is beneficial.

CHAPTER IV

SOIL GENETICS: THE SOIL FORMATION PROCESSES

The preceding chapters make it clear that the constituents of the parent materials of soils may be broadly grouped under four headings: (1) the strong bases (made up of the alkalies—soda and potash, and the alkaline earths—lime and magnesia), (2) the sesquioxides, (3) silica, and (4) organic matter. The fate of each of these four groups and the way in which one will influence the destiny of another is dependent upon the conditions under which the soil is formed. The conditions are for the most part climatic, but geological and other factors which may influence the state of wetness of the soil-forming area are also important.

The Russian pedologists more than any others, have studied the various processes which are involved in the making of soils, and it has become increasingly clear from their work, that in order to understand any particular soil area it is necessary to have some conception of the processes which have been, and still are, going on; and of the way in which the four groups of soil-forming materials are behaving.

The segregation of the bases from their original compounds (p. 27) is common to all soil formation processes. These processes fall into two groups, those in which air is excluded, and the conditions are *anaerobic*, and those in which aeration is effective and *aerobic*

activities take place. Anaerobic conditions prevail in water-logged areas, and the consequent depression of bacterial activity gives rise to an accumulation of organic matter which becomes dominant and imposes its characteristics upon the final product. Under these conditions the *Peats* are formed.

The soil formation processes which take place under aerobic conditions fall into three broad groups which are determined by—

(*a*) arid conditions;

(*b*) moist tropical conditions;

(*c*) cool humid conditions.

Under *arid conditions* where the potential evaporation exceeds the rainfall, the facilities for the leaching of soluble material are at a minimum, the bases which are split off during weathering tend to accumulate, remaining in the soil as salts and also in association with soil colloids (p. 90). In some arid areas this state of affairs is accentuated by the deposition of salts from bygone lakes.

Under some arid conditions both the alkalies and alkaline earths accumulate, giving rise to the *Saline and Alkali* soils. These soils fall into two groups, some containing alkali carbonates known as *Solonetz* soils and others containing mostly neutral salts which are known as *Solonschak* soils. An important development of the soil-forming process is involved in the solonetz on account of the tendency of the alkaline carbonates to dissolve the humus and carry it down to a lower layer. This lower humus-containing layer contracts on drying out, presenting a sort of columnar structure.

Under other arid conditions the alkali bases are for the most part removed from the surface soil and the alkaline earth bases accumulate, mainly as carbonates. Under semi-arid conditions which admit of consider-

able growth during the early and wetter part of the year but which do not admit of the rapid decay of the organic matter during the succeeding drought, organic matter accumulates forming the black earths or *Tchernozem* soils. Under somewhat more intensely arid conditions, the lack of moisture does not admit of much organic growth and the *Chestnut-coloured earths* are formed which are very deficient in organic matter.

Under *moist tropical conditions* there is a rapid decomposition of mineral material and the strong bases are leached in the form of carbonate or bicarbonate. These alkaline carbonates remove silica and in consequence the dominant constituents of the mineral part of the remaining soil are the sesquioxides. These conditions, moreover, bring about the rapid decay of organic matter and a consequent poverty of humus in the soil. In this way the *Laterite* soils are produced.

Under *cool humid conditions* such as prevail in this country, bases are leached, organic matter is partially decomposed and the products of this decomposition effect the leaching of the sesquioxides. These sesquioxides may be distributed throughout the weathering material giving rise to what are known as *Brown Earths*, or they may be deposited at a lower level leaving a bleached layer above and giving rise to *Podsol* soils.

These soil formation processes, which are here described only in the briefest outline, are summarized on page 43.

Podsol Formation. Under the conditions which prevail in this country the most important soil-forming process is that which involves in addition to the leaching of the bases, the carrying down of the sesquioxides. The mechanism involved here is still a little obscure, but empirical observation makes it clear that the

organic matter and the products of its decomposition are involved in the process. There are two general possibilities, either or both of which may be important.

1. The aqueous solutions of many organic substances have a remarkable solvent action on iron and aluminium compounds. For example $\frac{N}{20}$ oxalic acid will extract large amounts of iron and aluminium from a soil, while $\frac{N}{20}$ hydrochloric acid will frequently not dissolve sufficient to give a perceptible precipitate with ammonium hydroxide. This action is not confined to acids : the neutral and alkaline salts of many organic acids, the sugars and nearly all hydroxy-organic compounds will dissolve iron and aluminium from soils and minerals. The iron and aluminium dissolved by some of these substances cannot be precipitated by ammonium hydroxide and the iron dissolved by the hydroxy-compounds fails to give the usual red colour with thiocyanate. It is generally supposed that the iron and aluminium thus dissolved enter into a complex radical.

Decomposing organic matter will therefore tend to bring iron and aluminium into solution in the soil.

2. There is a further consideration. The hydroxides of iron and aluminium are capable of existing in colloidal solutions. These sols, however, are very sensitive to many electrolytes which precipitate them in the gel form, which is the form familiar to every student of elementary chemistry. Now in the absence of lime and the presence of water, humus tends to pass into a sol form, which, unlike the sols of iron and aluminium hydroxides, is not very sensitive to electrolytes. If a solution contains humus sol and the sols of iron and aluminium hydroxides, the humus will

CHAPTER V

SOIL PARTICLES

Chapter VI will make it clear that the soil particles are very much more elaborate than mere particles of rock. It is important, however, to consider in the first instance some of their properties *as particles.*

The Size of the Particles

A quite casual inspection of a number of soil samples makes it evident that in any soil there are particles of many different sizes, and that in some soils larger particles preponderate, in some smaller particles preponderate, while in others the larger and smaller particles are better balanced. The common and non-technical classification of the particles, according to their size, implies a division into two groups, *sand* and *clay.* The farmer recognizes light or sandy soils at one extreme, heavy or clay soils at the other, and between these extremes light, medium, and heavy loams.

Mechanical Analysis. For the scientific study of this matter, it is necessary to be more precise, and to consider the particles in various groups with properly defined upper and lower limits of size. In this country it is agreed to call all those particles whose diameters exceed 1 mm. "*Stones and Gravel.*" The material of greater importance is that which passes a 1 mm. sieve, and is called the "*Fine Earth.*" This is divided into five "fractions," as shown in Table 4.

TABLE 4

BRITISH MECHANICAL ANALYSIS FRACTIONS [1]

Name of Fraction.	Diameter in Mm.		Method of Separation.
	Max.	Min.	
Coarse Sand . . .	1·000	0·200	Sieving
Fine Sand	0·200	0·040	Sedimentation
Silt	0·040	0·010	Sedimentation
Fine Silt . . .	0·010	0·002	Sedimentation
Clay	0·002	—	Sedimentation

The Fine Silt fraction is sometimes further subdivided into "*Coarse Fine Silt*" (0·010–·005 mm. diameter), and "*Fine Fine Silt*" (·005–·002 mm. diameter). This division is the convention adopted in Great Britain. Unfortunately different conventional divisions are made in other countries.

The Coarse Sand is separated by sieving. The finer particles are separated by a variety of methods, all of which depend in some way upon the greater velocity of fall of larger particles through a column of water.

Particle Size and Falling Velocity. When spherical particles fall through a column of fluid, the velocity of fall and the radius of the particle are connected by the equation (known as Stokes' Law)

$$v = \frac{2gr^2 (\sigma - \rho)}{9\eta}$$

where v = velocity of fall.
r = radius of particle.

[1] Until 1926 a sixth fraction "Fine Gravel" (**3·0–1·0 mm.**) was included. A further modification has now **been made.** See *Jour. Ag. Sci*, xvii, 1928, 734.

σ = density of particle.
ρ = density of fluid.
η = viscosity of fluid.

This is the equation which is used in mechanical analysis to calculate what sizes of particles will fall through a column of water of a particular height in a particular time. There are, however, at least two facts which make the strict application of this equation to falling soil particles invalid: first, the soil particles are not clean cut particles of rock material with a definite radius, but, as will be seen in Chapter VI, are coated with gelatinous material which gradually merges into the surrounding water; second, the particles are not spherical. There are two ways in which the difficulties caused by these facts may be overcome.

1. The particles, not having a precise radius, are considered to be divided into groups according to their *effective* radius, i.e. the radius of spheres having the particular falling velocity in question. So that when it is said that the fine silt fraction is composed of particles whose diameters lie between 0·04 mm. and 0·01 mm., it is understood that they have the same velocity of fall as *spheres* in that range of diameters. This is the usual way out of the difficulty.

2. The fractions may be defined by the falling velocities, which is a real property, without any mention of a radius either real or imaginary. This method is used by Robinson. It is entirely rational and is presumably not in quite general use merely because older conceptions of the soil long ago established the use of the *size* of the particles in this connection. As a matter of convenience (see p. 51) the use of the *logarithm* of the falling velocity is preferable to the use of velocity itself. In this way the finer fractions are defined thus:—

Fraction.	Range of Velocity (v) cm./sec.	*log* v.
Silt . . .	0·100–0·010	$\bar{1}$–$\bar{2}$
Fine Silt . .	0·010–0·0001	$\bar{2}$–$\bar{4}$
Clay . . .	0·0001–	$\bar{4}$–

Robinson's Method. The method now in use in this country which is perhaps the simplest and most satisfactory of them all, is based upon the work of G. W. Robinson. The primary consideration involved in this method can easily be seen in the following way. If three different suspensions be made up of particles of three different sizes, each suspension will begin to clear from the top downwards as the particles fall. At any given time there will be a greater depth of clear water in the suspension containing the larger particles which fall more rapidly than in the suspensions containing smaller particles. If now, the three groups of particles are mixed together in one suspension, the same sort of thing will happen, so that at any given time there will be three positions in the suspension, one denoting the top of the column of large particles; above that will be the top of the column of medium particles, and above that will be the top of the column of small and most slowly falling particles. By introducing a pipette into such a suspension to appropriate depths and after calculated times of standing, it is possible to draw off—

(*a*) a mixture of all three grades of particles;
(*b*) a mixture of the medium and the small particles;
(*c*) the small particles only.

Fig. 2 will make this quite clear.

In Robinson's method this consideration is applied to the estimation of (1) silt and fine silt and clay, (2) fine silt and clay, (3) clay. The fine sand is estimated by decantation.

This method is also called the "pipette method" and the "A.E.A. (1926) method." The latter name arises from its official adoption in 1926 by the Agricultural Education Association.

Distribution Curves. The estimation of the percentage of particles belonging to each of the five fractions enables one to state with a certain amount of precision, the mechanical composition of a soil. However, the division into five fractions is, for many purposes, not sufficiently detailed. Two soils may each

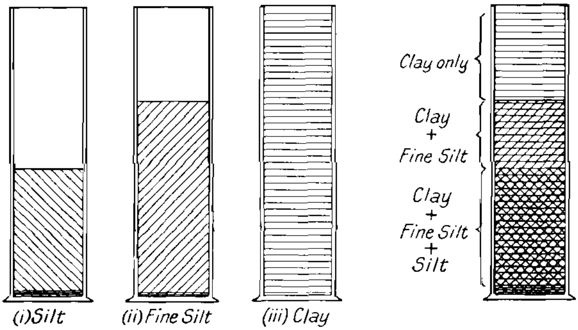


FIG. 2.—Diagrammatic Representation of the Settlement of Mixed Particles.

show the same percentage of clay, but one may be largely composed of particles whose diameters are only a little less than ·002 mm., while the other may have a preponderance of particles very much smaller. A difference like this which will have marked effects upon the properties of the soil, is not shown in the mere statement of the percentage of the clay fraction. It is possible, of course, to adapt the pipette method of mechanical analysis to further sub-divisions, but if this is carried too far, practical difficulties arise.

A different method of making a mechanical analysis

involves what is practically a process of continuous and automatic weighing, which can be carried out with the Odén-Keen balance, by which the times required for small successive weights of soil to settle out from the suspension are measured. From these data a curve can be constructed by which the percentages are plotted against the radius of the particle or some

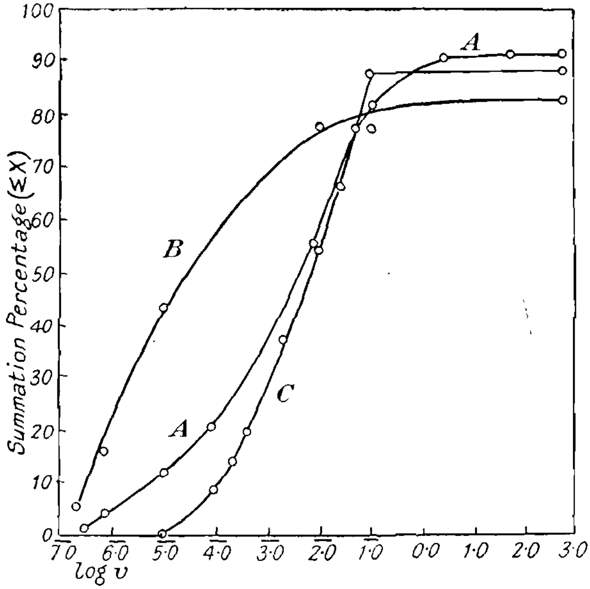


FIG. 3.—Principal Types of Mechanical Composition Curves (Robinson, *Journ. Agric. Sci.*, Vol. 14).

function of it and the percentage of particles of any radius can be found. This method involves an expensive apparatus, and is not available for general purposes.

A useful curve can however be obtained from results of mechanical analysis by the pipette method. Robinson has shown that if the logarithms of each of the various settling velocities are plotted against the per-

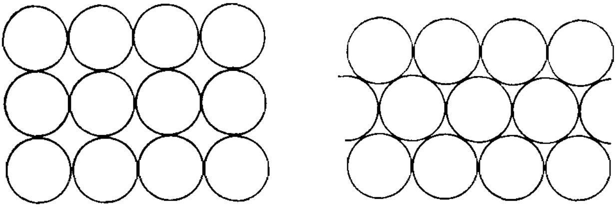
centages of *all* the particles having settling velocities less than each of them, the points fall on a smooth curve. Fig. 3 is taken from Robinson's paper. *A* is the most usual type of curve, *B* represents a very heavy soil and *C* is the curve for powdered slate. Such curves clearly give more detailed information and have the advantage of making it possible to take the results of the mechanical analysis expressed in accordance with the conventional divisions of one country, and translate them into the divisions adopted in another country.

In making these curves the logarithms of the velocities are used in preference to the velocities themselves because if velocities are used the "clay" part of the curve, which is the most important part, becomes too crowded and small.

The Arrangement and Aggregation of the Particles. There are two kinds of ways in which the arrangement of soil particles may be affected.

1. There are mechanical operations which compress a system of particles (e.g. rolling) or loosen the system (e.g. harrowing). The gross volume occupied by a system of particles will be made up partly by the particles themselves, and partly by the *pore space* between. Mechanical operations like rolling and harrowing influence the proportion of soil particle to pore space. The two extreme arrangements for a system of spheres of equal size, are shown in Fig. 4. In the arrangement *A*, the pore space will be approximately 50 per cent. of the gross volume, and in the arrangement *B* it will be approximately 25 per cent. A soil system, however, is different from such a system as this in at least three ways. First, the particles are not spherical, second, they are not all equal in size, and third, the particles are more or less bunched

together. A little consideration will show that th formation of bunches or crumbs will theoreticall permit a larger maximum pore space than 50 per cent that the various sizes of the particles will theoreticall allow a minimum pore space below 25 per cent., an that the irregular shape of the particles may act i either way. As a practical fact, however, the po space of soils rarely exceeds 50 per cent., except pe haps in a mulched surface, and it rarely falls belo



A. Pore Space ≏ 50% *B*. Pore Space ≏ 25%

FIG. 4.—Arrangement of Spheres.

30 per cent. Extensive measurements of pore spa have been made by King in America. The largest pe centage pore space is usually found in clays, and th lowest in sands. The pore space is obviously co nected with the difference between the *real speci gravity* of the soil (that is the specific gravity of th actual material of which the particles are made), an the *apparent specific gravity* (that is the specific gravit of the system of " particles plus pore space "). Th relation between these is

$$P = \frac{S - S'}{S}$$

where P is pore space, S and S′ the real and appare specific gravities respectively.

2. In addition to the purely mechanical ways in which the arrangements of the soil particles may be altered, there are other influences which bring about the formation or deformation of compound particles. Alternate freezing and thawing tends to cause particles to aggregate together, a fact of considerable practical importance, particularly on heavy soils. The heat of the sun acts in a very similar way, and so it comes about that whereas a farmer in this climate exposes his plough furrow to winter frosts, a farmer in tropical climates exposes it to the sun with very similar results. In both cases the increased tendency for the particles to aggregate together is probably due to the de-hydration of the colloids.

The effect of electrolytes on flocculation of the soil particles is sometimes very marked. The general effects are that alkalies tend to deflocculate the soil crumbs, whereas acids and neutral salts tend to flocculate them. If sodium hydroxide be added to one suspension of soil particles (previously extracted with acid to remove calcium), a neutral salt to another, and an acid to a third, it will usually be found that the particles bunch together and settle out relatively rapidly from the suspensions treated with acid and with neutral salt, whereas the particles in the alkali-treated suspension will remain suspended even longer than in an untreated suspension, because such aggregates of particles as existed there tend to be "dispersed" into their ultimate particles. Now in farming practice, it has long been known that the addition of lime to certain types of clay soil has an important effect in flocculating the clay particles, and so producing what is, in effect, a lesser number of larger particles, the soil being thereby rendered lighter and easier to work. The use of lime, which is an alkali, to floccu-

late soil particles in this way, is contrary to the general effect of alkalies as indicated above. The explanation of this apparent anomaly will appear later (p. 61).

In the field, particles are always to some extent aggregated into crumbs. Indeed the student who makes mechanical analyses of soil in the laboratory will know that a crucial operation is the pre-treatment of the soil (usually with acid and hydrogen peroxide) in order to obtain a maximum dispersion. Until recently this pre-treatment was not carried out effectively and many of the mechanical analyses of the past show too high figures for silt and too low figures for clay—aggregates of clay having been fractionated as silt.

The crumbs are normally formed with the larger particles inside and the smaller ones outside (see Fig. 8, p. 98).

The Chemical Composition and Mineralogy of Soil Particles

Table 5 summarizes the results of the complete analysis of the various fractions of soils obtained by (*a*) Hall and Russell, working with soils from the South-east of England, (*b*) Robinson, working with soils of North Wales, and (*c*) Hendrick and Ogg, working with drift soil in the neighbourhood of Aberdeen.

In the English soils it will be noted that the silica varies from about 95 per cent. in the fine gravel to about 85 per cent. in the coarser part of the fine silt. There is a curious drop in the silica content from the coarse fine silt to the fine fine silt. From the fine fine silt to the clay, the silica varies from about 65 per cent. to 50 per cent.

Consideration of the more detailed results of Hall and Russell's analyses further shows that in general, the

TABLE 5

The Composition of the Soil "Fractions"

Soil.	English (Hall and Russell).			Welsh (Robinson).			Scotch (Hendrick and Ogg).		
	SiO_2.	Al_2O_3 and Fe_2O_3.	CaO, MgO and K_2O.	SiO_2.	Al_2O_3 and Fe_2O_3.	CaO, MgO and K_2O.	SiO_2.	Al_2O_3 and Fe_2O_3.	CaO, MgO and K_2O.
Fine Gravel[1] . .	94·4	5·1	—	64·6	24·4	—	85·0	9·7	2·73
Coarse Sand . .	93·9	2·8	—	67·0	25·2	—	84·0	10·5	3·95
Fine Sand . .	94·0	3·2	2·1	75·8	19·4	—	73·9	17·7	5·83
Silt	89·4	6·6	3·4	74·7	22·4	—	70·2	19·9	4·69
Coarse Fine Silt .	84·1	9·8	4·5	62·9	34·3	—	67·2	26·8	5·59
Fine Fine Silt . .	64·3	26·9	7·9						
Clay	51·3	38·6	6·7	43·8	49·6	—	44·1	49·5	3·29

[1] See footnote, p. 46.

percentage of potash in the clay fraction is approximately one-tenth that of the alumina, and about one-thirtieth that of the clay, the alumina constituting about one-third of the clay.

The most striking point of difference between the composition of the Welsh and Scottish soils on the one hand, and the English soils on the other, is that the larger particles of the Welsh and Scottish soils contain less silica and more base than those of the corresponding fractions of the English soils. These differences appear to be connected with important differences in fertility. In England, agriculturists are accustomed to regard light soils as being unable adequately to provide certain plant foods, particularly potash, to the plant. The composition of the sand fractions of the English soils is in full agreement with this. In North Wales where larger soil fractions contain more base, the lighter soils are sometimes much less "hungry," and in less urgent need of potash, etc., than soils of similar texture in this country. The important processes of nitrate formation (p. 111) appear to go on satisfactorily in the soils of North Wales under conditions of lime deficiency which usually seriously impede the processes in English soils. This difference may be due, among other things, to the greater amount of base which the soil can provide.

The Mineralogy of Soils. The differences in chemical composition of the English soil particles on the one hand, and the Scotch and Welsh on the other, is a consequence of their different history. The Scotch and Welsh soils in question are *relatively* recent products of original rocks. The English soils are derived from sedimentary rocks and have had a longer and more chequered history during which particles originally together and derived from the same rock have be-

come widely separated. The differences in history and composition are consistent with differences in mineralogy. Hendrick and Newlands have examined the fine gravel, coarse sand and fine sand of several English and Scotch soils by dividing their constituent minerals into three groups :—

1. *Orthoclase group* (mainly felspar and muscovite).
2. *Quartz group.*
3. *Ferro-silicate group* (ferromagnesian minerals and oxides of iron).

Minerals of the orthoclase group were abundant in Scotch soils but were rarely present in English. The quartz group was more abundant in English than in Scotch soils. The ferro-silicate group was more prolific in the Scotch soils in which it was chiefly represented by silicates, than in the English soils in which oxides of iron were the chief members of the group.

CHAPTER VI

SOIL COLLOIDS

It was usual, until ten or fifteen years ago, to regard the soil particles as small pieces of rock material mixed with a certain amount of organic matter, and surrounded by a film of water. The analogy was frequently made between soil particles with the water around them, and a system of moistened glass beads. Experimental investigation of some soil problems, particularly those which concern soil water, has shown that such a simple system as "particle plus water film" is not compatible with the facts.

The Permeability of Soils. It is quite obvious that the permeability of a system of particles to a given fluid is dependent upon the viscosity of the fluid. Simple considerations show that the permeability (P) of any system to a particular fluid is inversely proportional to the viscosity (η) of that fluid, so that the product $P\eta$ is for any given system constant and independent of the fluid. Using small glass particles, Green and Ampt in Australia found that this relationship held. They determined the permeability (P_a) of the system to air, and the permeability (P_ω) to water, and found that

$$P_\omega \, \eta_\omega = P_a \, \eta_a \text{ or } \frac{P_a \, \eta_a}{P_\omega \, \eta_\omega} = 1.$$

With soils, however, this relationship did not hold by

any means, and $\frac{P_a \eta_a}{P_\omega \eta_\omega}$ was found to be **always** greater than unity.

The following are their results for three soils:—

	Sandy Soil.	Loam.	Clay Soil.
$\frac{P_a \eta_a}{P_\omega \eta_\omega}$	2·0	4·1	13·6

The divergencies of these figures from unity are greater the greater the amount of clay present.

These abnormal values can only be explained by assuming a low value for P_ω. For some reason water permeates the soil at much less than the calculated rate. Qualitatively this can be demonstrated by taking two vertical tubes, one containing clay, or clay soil, and the other containing sand, with one end of each tube placed in water. In accordance with the usual phenomena of capillarity the water will rise through the irregular channels between the particles, but instead of rising more rapidly through the narrower channels of the clay than through the wider channels of the sand, it will rise less rapidly—although after a long time it may rise to a greater height. This demonstrates the existence of some property which hinders the normal movement of water. The property is lost on ignition, and if a third tube be included in the above experiment, containing the same clay after ignition, it will be found that the water rises more rapidly through the narrower channels of the *ignited* clay than through the wide channels of the sand.

Green and Ampt concluded that the soil contains colloidal gelatinous matter which imbibes the water and, by swelling, restricts the capillary passages.

The Rate of Evaporation of Water from Soils. By the use of a balance specially designed for the

purpose, it has been shown by Keen that there are certain abnormalities about the rate of evaporation of water from soil. Water evaporates from sand and from china clay in accordance with the ordinary laws of diffusion. Evaporation from soil is more complicated and, as the water decreases, evaporation slows up to a much greater extent than the laws of diffusion would imply. There is therefore some property of the soil which opposes the force of evaporation. It is destroyed by ignition of the soil, for evaporation from ignited soil is quite normal. These observations, which have been extended and the interpretation of which has been modified by E. A. Fisher, have always led to the conclusion that the soil is a dual system composed partly of "particle" and partly of water-imbibing colloids.

The Freezing Point of the Soil Solution. It is well known that the freezing point of water is lowered by the presence of salts in solution. The basal law involved states that the depression of the freezing point is proportional to the concentration of the solution. If, therefore, a solution has a freezing point of $-\triangle$ °C., it will, after 50 per cent. of the water has evaporated and the solution therefore become twice as concentrated, have a freezing point of $-2\triangle$ °C. If the original V c.c. be reduced by evaporation of the water to v c.c., the freezing point should be

$$-\frac{V}{v}\triangle\ ^{\circ}\mathrm{C}.$$

The depression of the freezing point of the water in moist quartz sand and various types of soil has been examined by Bouyoucos. A few figures illustrating his results are given in Table 6. It will be seen that the solution permeating quartz sand obeys the law relating concentration to depression of the freezing

point reasonably well, but the soil solution in contact with the soil most obviously does not. When water evaporates from the soil, the depression of the freezing point increases far more rapidly than the law indicates.

TABLE 6

LOWERING OF THE FREEZING POINT OF QUARTZ SAND AND SOIL AT DIFFERENT MOISTURE CONTENTS (Bouyoucos)

	Quartz Sand.			Sandy Loam.			Clay Soil.		
Per Cent. Moisture.	18	10	2	21	15	7	34	24	18
Depression of F.p. (° C.) . . .	·009	·018	·091	·023	·065	·390	·034	·212	·922
Depression of F.p. calculated from that at highest water content .	—	·016	·081	—	·035	·075	—	·048	·064

Evidently the soil solution becomes far more concentrated on evaporation than would be expected. This is only likely to happen if some part, and not the whole, of the water behaves as an ordinary solution. Bouyoucos concludes that a part of the soil water is "free," and contains the dissolved material, while part is "unfree." "Unfree" water is held in some such way that it does not participate equally with the "free" water in the phenomenon of solution. Whatever the precise interpretation, the facts show that the relation of the soil particle to the surrounding water is complex.

The Flocculation of Soils by Lime. It has already been mentioned (p. 53) that lime has a marked power of flocculating clay particles, and that this

appears to be anomalous in so far as alkalies normally hinder flocculation. If the effects of a neutral potassium or sodium salt be compared with those of the corresponding hydroxide by adding the equivalent amounts of each to suspensions of clay, it will be found that the neutral salt brings about a flocculation and consequent settlement of the particles, while the alkali keeps the particles suspended longer than in an untreated suspension. If, however, the effect on a clay suspension of a neutral calcium salt be compared with that of calcium hydroxide, it will be seen that the calcium hydroxide is a better flocculant than the neutral salt. Moreover, this abnormality is only found when suspensions of *clay* are used. If the experiment be repeated with suspensions of *silt* particles, it will be found that the neutral calcium salt is a better flocculant than the calcium hydroxide.

Until it was recognized that the soil particles have gelatinous colloids over their surfaces, it was impossible to explain this action of calcium hydroxide on the clay. When, however, the colloids are taken into account the explanation is obvious in a general way. Such colloidal substances as silica, humus, etc., which occur in soils are precipitated from their "solutions" or "sols," by calcium and other alkaline earth compounds when the medium is alkaline, but not when the medium is neutral or acid. The gelatinous bodies around the soil particle will tend, at their surfaces, to produce sols with the surrounding water: the addition of a neutral calcium salt will not affect this sol, but in the presence of an alkali, calcium compounds will precipitate these sols forming a gelatinous mass which entangles the particles in bunches.

Calcium hydroxide being an alkali, is a poor flocculant of the "cores" of the particles, but, for the

reasons explained above, it is an excellent flocculant of the gelatinous matter surrounding those cores. With clay particles, where the core is very small and the colloids relatively great, the precipitating action of calcium hydroxide on the colloids will dominate its deflocculating tendencies on the cores of the particles. With silt particles, where the cores are larger, and the colloids relatively little, the action on the cores of the particles will override the tendency of the hydroxide to precipitate the colloids.

The Shrinkage of Soils. If clay or a clay soil is uniformly moistened and then allowed to dry out, it will shrink and crack. This is true generally of particle systems. It has recently been shown by Haines at Rothamsted that the diminution in volume as the clay dries out is exactly proportional to the amount of water which is evaporated until the amount of water remaining reaches a certain critical amount. After this the amount of shrinkage becomes much smaller in relation to the water lost. This, however, is not true of moist kaolin (which has no colloidal properties), the shrinkage of which continues to be proportional to the water lost so long as there is any shrinkage (see Fig. 5). When, however, kaolin has colloidal properties imposed upon it, by coating the particles with some gelatinous material such as silica or gelatine, it then shows the "residual shrinkage" which characterizes soils.

In this connection the Rothamsted workers have shown that when the residual shrinkage of clays and clay soils commences, air enters. If after this, the soil is remoistened, it absorbs water and swells, but its volume for any given water content is greater than during the original process of drying, there now being air present in addition to the clay and water. If the

clay or soil is now allowed to dry out a second time, its volume at the end of drying out is greater than at the end of the first drying out. At this stage the soil tends to crumble. In order, therefore, that a furrow slice shall crumble properly, it is necessary that it shall dry to a point beyond that at which residual shrinkage sets in, and at which air enters the mass, and that it shall be re-wetted and dried again.

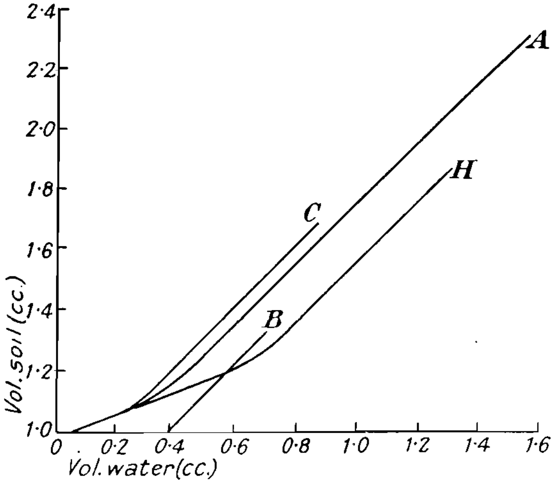


FIG. 5.—Shrinkage of Soil (Haines, *Journ. Agri. Sci.*, Vol. 13).
A = Clay separate. *B* = Kaolin.
C = Clay (Sudan). *H* = Peaty Soil.

The Effect of Heat on the Extractable Constituents of Soil. It was noted many years ago that if a soil is gently heated over a bunsen burner for a few minutes, the amounts of iron, aluminium, phosphate and other constituents which can be extracted by dilute acid, are considerably greater than the amounts extracted in the same way from the non-heated soil. No reasonable explanation of this could

be put forward at the time it was observed. The increased quantities dissolved from the heated soil must be due to one of two general causes. Either iron, etc., compounds have been converted into some more soluble form, or else a greater amount of the surface of the particles containing these compounds has been exposed to the attacking acid. The first of these is a most unlikely explanation, for the effect of heat upon such compounds as are here involved is usually to depress their solubility. A greater exposure of the surface of soil particles must therefore be brought about by this gentle heating. Now if the soil particles, all having gelatinous coatings, are bunched together in the soil, the effect of a gentle heat will be to dehydrate and shrivel up this gelatinous material, as a result of which the particles will tend to fall apart and to admit the easy access of an acid solution subsequently applied. Particles (e.g ferric hydroxide), which are artificially coated with gelatinous silica, show this same phenomenon of giving up a greater amount of iron to an extracting acid after gentle heating.

It will be seen from the foregoing considerations that the soil colloids are responsible for many important and characteristic properties. They are responsible for the enhanced tendency of the soil particles to retain water, a property which is a great inconvenience when a soil contains a very high percentage of colloidal clay, but which is of inestimable importance in soils of medium and light texture. They are responsible for the residual shrinkage of soils which is so intimately connected with the proper crumbling of the plough furrow. They are responsible for the amelioration in the texture of clay soils which is brought about by liming.

The colloids also play an important part in the

retention of bases, such as lime, potash, etc., in the soil, and indirectly of certain acids, notably phosphoric acid. This will be discussed in Chapter VII.

Not a great deal is known about the composition of soil colloids. They are formed during weathering and may be presumed to be composed of silica, sesquioxides and aluminosilicic acids. There is some evidence that colloidal aluminosilicic acids are mainly responsible for the absorption of bases.

CHAPTER VII

SOIL WATER

A soil which has been deprived of all its water by oven-drying, will, when left in contact with the air, take up a certain amount of *hygroscopic* water. The amount so taken up will depend upon the temperature, the vapour pressure, and the soil. If the soil is then placed on a perforated plate so that free drainage is possible, and water is poured over it, it will become visibly wet, retaining a further amount of water in the form of films around the particles. This is called *capillary* water. Water in excess of the hygroscopic and capillary water will be free to move under the action of gravity, and is therefore termed *gravitational* water. The rough classification of soil water under these three headings is fairly obvious: it has been recognized for a long time, and has served as the basis of more detailed investigations. These more detailed investigations may conveniently be considered under two headings: first, the attempts to establish moisture "constants," and second, the attempts to establish a more detailed "classification" of the soil moisture. It will become apparent later that there is nothing fundamentally different between these two groups of investigations.

THE MOISTURE CONSTANTS OF THE SOIL

Efforts have been made to define and determine some constants which shall characterize the moisture

relationships of particular soils and indicate the ability of soils to hold water and to supply water to the plant. Following is a brief account of the chief of these.

The Maximum Water Capacity. This is the most obvious and the most easily measured. It is the maximum amount of water which the soil can hold when drainage is entirely precluded and the air is wholly displaced. It is, in fact, the pore space, and was used by King to measure the pore space. The outstanding general features of his results have already been mentioned (p. 52).

The Moisture-Holding Capacity. The next most obvious thing to measure is the maximum amount of water which a soil can hold when it is drained as freely as its texture will allow. That is, the maximum amount of water which can remain in a soil when all external factors which deter drainage have been removed and when the only hindrance to free drainage is inherent in the soil itself.

A number of measurements were made by Hilgard, and later by Briggs. In the simplest form of their method a vessel with a fine cloth bottom is filled with the soil and the weight of the filled vessel determined. The soil is then saturated with water and after drainage has ceased the weight is again taken. The increase in weight is a measure of the moisture-holding capacity.

Table 7 shows some figures given by Mosier and Gustavson of the University of Illinois. Both the maximum water capacity and the moisture-holding capacity are given, and the difference between the amount of water present when the soil is fully water-logged, and the amount remaining when it is freely drained, is surprisingly small. But it is recognized that under the experimental conditions in which the soil sample is detached, the amount of water held

TABLE 7

MAXIMUM WATER CAPACITY AND MOISTURE-HOLDING CAPACITY (Mosier and Gustavson)

	Sand.	Yellow Silt Loam.	Volcanic Ash Soil.
Maximum water capacity	29·23	52·10	64·49
Moisture-holding capacity	27·80	48·31	60·00
Difference	1·43	3·79	4·49

is decidedly greater than under field conditions in which the water is continuous down to the water table. It has been found that some soils held from 1·5 to 2 times the amount of water under the conditions of Hilgard's experiment than was found in the same soil in the field after heavy rain.

King made some determinations of "the amounts of water which were found in three types of soil with the undisturbed field texture, when they contained as much as they would retain after a few days of drainage following heavy rains." Some of King's results are shown in Table 8.

TABLE 8

MOISTURE-HOLDING CAPACITY UNDER FIELD CONDITIONS (King)

Depth.	Sandy Loam.	Clay Loam.	Humus Soil.
	Per cent.	Per cent.	Per cent.
First Foot	17·65	22·67	44·72
Second Foot . . .	14·59	19·78	21·24
Third Foot . . .	10·67	18·16	21·29

It is difficult in these experiments to fix the time at which drainage may be regarded as complete. King thought it probable that drainage was still going on even after sixty days. Furthermore, the amount of water held varies enormously, as would be expected, with the height of the soil above the water table.

The Maximum Capillary Capacity. Instead of saturating a soil and then allowing the gravitational water to drain away, as in the determination of the moisture-holding capacity, the opposite procedure suggests itself. Accordingly, experiments have been made to determine the maximum amount of water which can be lifted by a column of soil. King made some determinations by standing 12-inch columns of various soils and subsoils in water so that 11 inches of the column were above the water level. The conditions of the experiment were arranged to preclude loss by evaporation. The following figures are some of the results obtained:—

	Per cent.		Per cent.
Clay loam	32·2	Clay and sand . . .	22·6
Reddish clay . . .	24·5	Fine sand	17·5

The Hygroscopic Coefficient. When a dry soil is in contact with an atmosphere saturated with water vapour, the percentage of water taken up by the soil is the hygroscopic coefficient at that temperature. Hilgard made determinations of this coefficient by estimating the maximum amount of water taken up by a layer of soil. The amounts of water absorbed varied from 2 or 3 per cent. in light soils to 13 per cent. and more in heavy soils. Other determinations have been made by Mitscherlich, who places the soil over 10 per cent. sulphuric acid in a vacuum desiccator.

Two suggestions have been made about the value of the hygroscopic coefficient :—

1. It has been suggested that water in excess of the hygroscopic water is the water available for the plant, and that by estimating the total water in a soil and deducting the hygroscopic water the available water is determined.

2. Mitscherlich has discussed the value of the hygroscopic coefficient as a measure of the surface of the soil particles. He holds that it evaluates the soil texture in a better way than the mechanical analysis and affords a useful basis upon which to classify soils. Among the results obtained on these lines is one set for example, which indicates that, taking the surface of a given weight of quartz sand as unity, those of equal weights of a sandy soil, a loam and a clay soil are about 35, 90, and 750 respectively. A development of this way of measuring soil surface has been made by Mitscherlich. He estimates the outer surface of the *crumbs* by substituting the vapour of some organic liquid (e.g. benzene, or carbon tetrachloride) for that of water. These organic vapours, it is said, condense only on the *outer* surface of the compound particles.

Besides the practical difficulties of these estimations of hygroscopicity, a difficulty of interpreting the results arises from the complexity of the soil surface, and the impossibility of isolating from all secondary actions a pure hygroscopic effect.

Some determinations have been made of the heat developed when a dry soil is wetted, and attempts have been made to correlate this heat of wetting with the hygroscopic coefficient. The same difficulty arises, namely that the production of heat during the wetting of soil is a complex of chemical and physical actions.

The Moisture Equivalent. Another experimental method which has been adopted in the search for characteristic soil moisture constants is the removal

of as much as possible of the water by some arbitrarily fixed and measurable force, and the estimation of the remainder. The removal of water by a known force was effected by Briggs and McLane in the United States by centrifuging. After centrifuging under fixed conditions such that the force withdrawing the water was 3,000 times the force of gravity, they estimated the percentage of water remaining in the soil, and termed the figure the "moisture equivalent" of the soil. The moisture equivalent is therefore the percentage of water a soil can hold which necessitates a force greater than 3,000 g to remove it. Briggs and McLane determined this constant for over 100 soils. Its value was as low as 3–4 for coarse sands, and as high as 45–47 for heavy clays.

Moreover, Briggs and McLane evaluated the share of the various soil constituents in holding this water. They found that in one type of soil each 1 per cent. of clay (diameter less than 0·005 mm. in U.S.A.) is responsible for a moisture equivalent of 0·62, and each 1 per cent. silt (diameter less than 0·05 mm. in U.S.A.) for a moisture equivalent of 0·13; and as a corollary to this, they put forward formulæ connecting the moisture equivalent with the mechanical composition of various soil types.

The Wilting Coefficient. None of the determinations so far considered directly involve the plant. The measurement of a soil moisture constant which directly involves a plant effect was attempted by Briggs and Shantz, who determined the amount of water still remaining in various soils when "permanent" wilting had just set in. They subsequently correlated this "wilting coefficient" with the hygroscopic coefficient and the moisture equivalent, stating that—

Hygroscopic coefficient = 0·68 × wilting coefficient.
Moisture equivalent = 1·84 × ,, ,,

The wilting coefficient, like the moisture equivalent, can also be correlated with the mechanical analysis. One formula given by Briggs and Shantz is—

Wilting coefficient = 0·01 Sand + 0·12 Silt + 0·57 Clay.

These formulæ are, however, not generally applicable. The numerical factors need to be altered for alterations in the type of soil.

The Optimum Moisture Content. This term is usually defined as the percentage of water required in the soil for the optimum growth of plants. The term is sometimes used to describe the amount of water required for the best physical condition of the soil. This may mean very much the same thing, for although the amount of water transpired by plants varies considerably from one plant to another, it is probable that it would be as efficient, if not more efficient, to supply those plants requiring larger amounts of water more frequently, and to maintain in the soil the optimum amount of water required for physical soil conditions.

The Water Content at the "Sticky Point." If dry soil is mixed uniformly with increasing quantities of water the mixture becomes stickier and more plastic up to a certain point. Beyond this point further additions of water will make the mass more fluid until ultimately it becomes a mobile suspension. The water content at the point of maximum plasticity or, as it is frequently called, the "sticky point" has been used by Hardy and others as a soil characteristic. The percentage of water at this point will depend partially and perhaps almost wholly, upon the colloid

content of the soil and is likely to be a useful criterion of the colloidal properties of a soil.

The difficulty of determining when moistened soil is at the sticky point is not so great as might appear even when the determination is made by merely feeling with the hand.

The Capillary Transmission Constant. The moisture constants so far described are measurements of water in a static condition ; they are measurements of *amounts of water* retained by the soil under certain more or less artificial conditions. These statical measurements are valuable, but the water in the soil is practically never in a state of equilibrium. It is subjected to many varying forces, and is always in motion in a manner which will be outlined in the last section of this chapter. In recognition of the fact that the soil water problem is dynamic and not static, an interesting attempt has been made by Gardner in the United States to measure the " capillary transmission constant." This is a measure of the power of the soil to permit the movement of water through it, in somewhat the same kind of way as the specific electrical conductivity measures the power to conduct electricity and the specific thermal conductivity measures the power to conduct heat. Gardner has made a number of measurements, and further investigations of the soil water along these lines is likely to provide a very useful and characteristic figure for a given soil.

The " Classification " of Soil Water

The rough division of soil water into hygroscopic, capillary and gravitational water has already been mentioned. Some efforts have been made to elaborate this classification and these efforts are largely associated

with the work of Bouyoucos on the freezing point of soil water. By means of a dilatometer Bouyoucos measured the increase in volume consequent upon the freezing of water in the soil, and found that the increase in volume near the ordinary freezing point of water only corresponded to a part of the water becoming ice. Proceeding to lower and lower temperatures he found that more and more of the water continued to freeze but even at the lowest temperature at which he worked—78°, not all the water froze. Attempts were made to discriminate between the "free" water which freezes in the neighbourhood of 0°C. and the "unfree" water which freezes at lower temperatures, and to subdivide further the unfree water into capillary and combined water. All such classification is, however, arbitrary: the essential fact that emerges from these attempts to classify water is that the soil holds some of its water with very great force probably corresponding to something of the order of a thousand atmospheres pressure, and that there is a gradual transition from this to the free water.

It will therefore be seen that there is nothing fundamentally different about the conception of moisture "constants" of soil and the arbitrary "classification" of soil water. The attempted classification shows that the water is held with increasing force as it is nearer to the centre of the particle. Such moisture constants as the moisture equivalent, the wilting coefficient, etc., measure the amount of water that soil is able to hold against a particular force tending to remove it.

The System "Soil—Soil Water." From all that has been said of the surface of the soil particles, of the aggregation of those particles, and of the soil water, it will be clear that from the core of the particle

to the water percolating the soil under the action of gravity, there is a gradual transition. The larger particles in the centre of the soil crumb merge gradually into the finer clay particles; these pass by stages of more and more hydrated gel material into water which becomes more "free" as it is further removed from the "solid" material.

The earlier conception of a solid particle surrounded by a film of water and with a relatively sharp interface between solid and liquid led to a number of attempts to remove the soil solution from the solid (p. 127). The displacement of this solution by oil, the use of very high pressures, and the contact of absorbants with the soil, are methods which have been adopted. It is now realized, however, that whatever may be the value of the solutions so obtained, those solutions cannot be regarded simply and wholly as the nutrient solution of the plant, the composition of which is a direct index of fertility.

In the preceding consideration of the constitution of the soil, it has been necessary to consider separately the structural basis, the surface of the particles, and the soil water. But there can be no exact analysis of the system in such a way. The present evidence on the subject gives little justification for attempting to isolate the soil solution or even to contemplate it apart from the soil. This has been pointed out with some emphasis by Keen, who states that "the point which really needs emphasis in all studies of the soil solution is the recognition that the system *Soil—Soil Water* must be treated as a whole . . . considerations of surface films distributed over an inert mineral framework . . . are insufficient to explain the observed facts."

The Movement of Soil Water

It is sometimes implied that the rise of water in the soil takes place in consequence of the pore space between the particles acting as capillary tubes through which the water rises exactly as in glass tubes dipping into a bulk of water. But that cannot precisely account for the movement of water in a normal soil, for several reasons. The most obvious reason is that if the water rose in the soil in that way, the whole pore space would be filled with water—the soil would be waterlogged—which it normally is not.

It is the movement of water in a film over the surface of particles which may be taken to illustrate in its simplest form the mechanism of the movement of capillary soil water. It will be clear, however, that the movement of the soil water will be more complicated than that depicted in the ideal case. The whole of the water around the soil particles is not susceptible to this capillary movement in this simple way. The nearer the water is to the particle the more it is under the influence of the strong absorptive power of the colloidal surface of the particle, and the less it is susceptible to the capillary movement. The capillary water—the "free" water of Bouyoucos—merges into the gravitational water on the one hand, and into the "unfree" water on the other.

Besides the absorptive power of the soil, there are the following forces acting upon the film of water which is spread over the particles of a moist soil: (i) the forces due to the different pressures of differently curved surfaces; (ii) evaporation from the top layer of the soil; (iii) the absorbing action of plant roots; (iv) the force of gravity tending to pull the water downwards.

When water is removed by evaporation or by the

plant, water from other parts of the soil is moved by the difference of pressure set up, in order that the equilibrium may be recovered. It is clear, however, that there will seldom, if ever, be a static equilibrium established for any length of time. Such equilibria are always being disturbed by evaporation and by other causes of the removal of water.

It must be added that on account of the pull of gravity the film of water will be thicker (and the concavity between the particles therefore less) the lower it is from the surface. If the causes of water removal are annulled and a static equilibrium allowed to remain, that equilibrium will be such that the difference of pressure between the lower less concave surfaces and the higher more concave surfaces—a difference of pressure tending to move the water upwards—is exactly balanced by the force of gravity which tends to pull the water downwards.

At a depth which depends upon the underlying rock and other circumstances, the amount of water will be such as to fill the entire pore space between the particles of subsoil or rock. From this water level films of decreasing thickness rise upwards covering the soil particles.

Soil Texture and the Movement of Water. The upward movement of water in the soil is dependent upon the pressure gradient. The pressure gradient arises, after allowance has been made for the pull of gravity, because the concavity of the film between the particles near the surface is greater than it is lower down. This at any rate will be the condition when evaporation is taking place at the surface. Now the concavity of the film between the particles depends upon two things: (i) the amount of water: the concavity will be greatest where the amount of water is

least ; (ii) the size of the particles : the same amount of water in a given volume of particles will clearly make very concave surfaces between small clay particles, and fewer less concave surfaces between large sand particles. Hence it comes about that the water-lifting power of a soil is dependent upon the texture of the soil. Clay soils have a greater lifting power than sandy soils, and will lift water to a greater height. The number of vertical films which culminate in a given area will manifestly be greater in a clay soil than in a sand. A clay soil, therefore, has a greater water-lifting and water-holding power than a sandy soil, and a clay soil containing a greater amount of water can lift water from a sandy soil containing a smaller amount.

The Continuity of the Film. The movement of capillary water which has been described and discussed is clearly dependent upon the continuity of the film over the surface of the particles. If the film becomes broken, water cannot pass, at any rate not in the same way, beyond the point at which it is broken. In agricultural practice this way of setting a limit beyond which the water cannot go is used by making a *mulch* on the surface of the soil. If the surface layer of soil is mulched or loosened, the water film is broken and water cannot move through the region of the broken film. In this way water may be conserved below the surface of the soil and an undue loss by evaporation may be prevented in dry weather. Sometimes it is desirable to bring water into the surface layer—during the germination of seeds in dry weather for instance. The opposite procedure is then adopted and the soil is rolled and compressed in order to give every facility to a *continuous* film, and a consequent upward movement of the water.

The rolling of a *dry* soil will not do much to *restore* the continuity of a broken film, but if the soil is moistened by rain as well as rolled, the continuity of the film will be established and water will rise to the surface. Water may therefore be brought to the surface in greater amount than actually falls on it as rain. A mere shower may be just sufficient to re-make a broken film and the film will then serve as a means of bringing water up from below. Bringing water to the surface, however, will mean a greater loss by evaporation. In hot weather this may ultimately mean that soil which has been slightly wetted may become drier beneath the surface than adjacent and similar soil which has not been wetted. This paradox is pointed out by Hall, who states that if one portion of a dry garden soil be *slightly* watered in very dry weather it will soon become *drier* beneath the surface than an adjoining portion not watered at all. The slight watering is just enough to re-establish the continuity of the film to the surface, where in hot weather evaporation is rapid and water is speedily moved up and lost. Where the surface remains unwetted and the films broken, evaporation cannot so easily deprive the lower layers of their moisture.

CHAPTER VIII

SOIL AIR

The pore space of a soil normally contains air. This atmosphere is necessary for the respiration of plant roots and of soil organisms. In this chapter some salient facts about the composition of this air will be described.

The General Composition of Soil Air. The first important attempt to analyse the soil air was made in France about seventy years ago. Later, and with the advantage of new methods of analysis, a number of analyses have been made, and in 1915 the results of an important and systematic investigation of the subject carried out at Rothamsted by Russell and Appleyard were published.

The recent investigations in Germany, America and England all consistently indicate that the composition of the soil air is not vastly different from that of ordinary air. The following figures show the approximate composition of dry soil air and dry atmospheric air. The figures are percentages by volume.

	Soil Air.	Atmospheric Air.
Oxygen	20·6	20·99
Nitrogen, etc.	79·2	78·95
Carbon dioxide	·2	·03

The difference between the average composition of dry soil air and that of dry atmospheric air is not great. There are, however, three things to be mentioned.

1. The soil air contains seven or eight times as much carbon dioxide as atmospheric air.

2. The variation in the composition of soil air is considerable when compared with the variation in the composition of atmospheric air.

3. The soil air is generally saturated or nearly saturated with water vapour.

The Cause of the Relatively High Carbon Dioxide Content of Soil Air. The main cause of the comparatively large percentage of carbon dioxide in soil air is the activity of micro-organisms. This is indicated in two ways.

Firstly, the treatment of the soil with antiseptics prohibits the further production of carbon dioxide.

Secondly, the fluctuations in the amount of carbon dioxide are roughly parallel to the fluctuations in the amounts of other products which are known to be the result of micro-organic activity. Several American workers have independently studied the relation of the production of carbon dioxide to the production of ammonia. Russell and Appleyard studied the relation of the production of carbon dioxide to the production of nitrate and also the relation of both the production of carbon dioxide and of nitrate to the bacterial numbers. There is a rough parallelism between the carbon dioxide produced, the nitrate produced, and the bacterial numbers. The curves are not absolutely parallel but they are sufficiently similar to justify the conclusion that all three things are related. Furthermore, that conclusion is consistently supported by the results obtained in America.

The soil air is in contact with the atmospheric air and there must therefore be a continuous diffusion tending to equalize the composition of the whole connected system. In certain exceptional circumstances

this diffusion may become pronounced and dominate the other process. Generally, however, the production of carbon dioxide which accompanies the activities of micro-organisms is the dominant process, and while its result is modified to a varying extent by other processes, it is mainly responsible for the relatively high carbon dioxide content of soil air.

Variations in the Composition of Soil Air.

Variation with Season. Russell and Appleyard found in all their experiments, that the carbon dioxide content of the soil air—

(i) Rises to a maximum in spring.

(ii) Falls to a minimum in summer.

(iii) Rises to another maximum in autumn, which maximum is, however, not so high as the spring maximum.

(iv) Falls to its lowest minimum in winter.

Moreover, other investigations by Russell show a similar rise in biochemical activity in spring and autumn. Fig. 10 (p. 112) also illustrates this. It may be taken as quite general that the percentage of carbon dioxide in the soil air—along with other manifestations of biological activity—rises to a maximum in spring and autumn, the spring maximum being the higher.

It is difficult to attempt any final or detailed analysis of the effects on carbon dioxide production of each of the various factors, such as temperature, moisture, etc., which characterize seasons. There are, however, two points put forward by Russell and Appleyard.

1. From about November to May the temperature seems to be the dominant seasonal factor, and the increase in carbon dioxide is parallel to the rise of temperature. Between May and the following November, other factors dominate the production of carbon dioxide, for the temperature rises and then falls during

this period while the percentage of carbon dioxide falls and then rises. The two changes then become parallel again until the following spring.

2. The amount of *moisture* in the soil has a surprisingly small effect on the carbon dioxide content, but the amount of *rainfall* has a distinct effect. The falling of rain is more than a mere addition of water. The rain has oxygen dissolved in it, and the temporary saturation of the upper layers of the soil will disturb the normal course of diffusion.

Variation with other Factors. The seasonal variation is the chief and the best defined variation in the carbon dioxide content of soil air. Russell and Appleyard found little or no evidence of variations due to strong winds, changes in atmospheric pressure or to the change from night to day. After sudden changes of temperature there is little difference between the carbon dioxide content of atmospheric and soil air. Organic matter causes an increase in the amount of carbon dioxide as might be expected, but the effect of a growing crop is surprisingly small and is frequently quite negligible. Ploughing—particularly early ploughing—decidedly reduces the carbon dioxide.

The Absorbed Air of the Soil. Russell and Appleyard found that after evacuating a flask containing soil, their manometer continued to fall, indicating that in addition to the "free" atmosphere of the soil there is an "absorbed" atmosphere which is slowly given up to a vacuum. Their investigation of this atmosphere showed that it contained only insignificant amounts of oxygen. The first portions that were extracted contained carbon dioxide and nitrogen in variable amounts, subsequent extractions withdrew almost pure carbon dioxide.

CHAPTER IX

SOIL TEMPERATURE

For any biological process taking place under given conditions there is a *maximum* temperature above which the process ceases, a *minimum* temperature below which it ceases, and an intermediate *optimum* temperature which is most favourable to the process. The soil is the medium of manifold biological processes which act and react upon one another. These interrelated activities are all influenced by temperature and the temperature of the soil is therefore an important factor in determining their net result.

Temperature and the Growth of Plants. Table 9 contains some data published by Haberlandt which make clear the important effect of temperature on germination.

TABLE 9

NO. OF DAYS REQUIRED FOR APPEARANCE OF RADICLE AT DIFFERENT TEMPERATURES (Haberlandt)

	40° F.	51° F.	60° F.	65° F.
Wheat . . .	6	3	2	1·75
Oats . . .	7	3·75	2·75	2
Vetches . .	6	5	2	2
Sugar beet .	22	9	3·75	3·75

Germination is much slower at the lower temperature

and slowly germinating seeds are very susceptible to fungoid and bacterial attacks.

The range of temperature over which germination will take place, and the optimum temperature of germination vary a little from one plant to another. For the germination of the seeds of the commoner crops, the minimum temperature is about 40° F., the maximum about 100° F., and the optimum about 85°–90° F. The temperature range and the optimum temperature for the subsequent growth of the plant are not usually much different from those for germination.

The growth of a plant is an enormous complication of physical, chemical, and biological processes. Each of these is affected to some extent by temperature, and the influence of temperature upon the growth of plants is a net result of its influence upon the permeability of cell walls, the activity of enzymes, the rate of transpiration, and all such conditions and processes.

Temperature and Micro-organisms. The fertility of the soil is very largely dependent upon the activity of micro-organisms. Apart from the normal influence of temperature on each of these activities, changes of temperature affect the proportion of the various organisms present. When the temperature reaches about 95° C. complicated effects ensue which are more conveniently considered later (p. 117).

Variations in the Temperature of a Soil. Under the influence of the sun, the surface of the soil is warmed. The heat is conducted downwards below the surface, but not to a very great depth. At depths of two or three feet the heating effect of the sun is not appreciable. The surface reaches a higher maximum temperature than air temperature, and it reaches that maximum temperature soon after the air reaches its maxi-

mum temperature, that is soon after midday. The maximum temperature attained below the surface is *lower the greater the depth. Not only is it lower than* the maximum at the surface, but it is attained later in the day.

By means of a continuous recording thermometer, records are made at Rothamsted of the temperature changes 6 inches *below the surface* of an uncropped soil. A discussion of the results for a period of one year has been published by Keen and Russell. The following are some of their chief conclusions.

The variations in soil temperature in summer are quite different from those in winter.

Summer Soil Temperature at 6 *inches Depth.* There is a marked daily variation in soil temperature during the summer. At a depth of 6 inches the daily rise begins about 9.30 a.m. and continues until about 4.30 p.m. The maximum then reached is maintained for a short time, after which the temperature falls, more slowly than it rose, until about 7.30 p.m.

The mean temperature is passed about midday and midnight. From midday to midnight is therefore the warmest period in the soil.

The maximum temperature at 6 inches is attained about 3 hours after the maximum temperature in the air. It is usually about the same as the air temperature, and at Rothamsted was about 22° C. (At the surface of the soil the maximum temperature is, of course, higher than the air temperature.)

The minimum temperature at 6 inches is attained about 7.30 p.m. and is 6°–8° C. higher than the air minimum, and at Rothamsted was found to be about 18° C.

Winter Soil Temperature at 6 *inches Depth.* In winter there is no regular daily variation of soil tem-

perature as there is in summer. A variation may continue over a period of several days.

The temperature at 6 inches is never quite as high as the air temperature.

The minimum temperature is generally about 3° C. higher than the air minimum. The minimum soil temperature is reached later in the day in winter than in summer: usually about 10.30 a.m. The air minimum is attained about the same time all the year round.

The change from winter to summer variations is fairly sharp.

The Difference of Temperature between one Soil and another. Two different soils, which are similarly situated geographically, may attain different maximum temperatures during the same day and under the same heating influence of the sun. There are at least three factors which may cause this difference.

(*i*) *Colour.* The percentage of heat energy absorbed by a black surface is well known to be greater than that absorbed by a white surface. Hence dark-coloured soils may attain a slightly higher temperature than light-coloured soils which are otherwise similar. This consideration is not of great practical importance, except in dry soils with very marked colour differences.

(*ii*) *Aspect.* It is fairly obvious that any surface at right angles to the sun's rays receives more heat per unit area than a surface at any other angle. On this account a southern slope (in the northern hemisphere) has the advantage of being warmer and "earlier" than level ground or northern slopes of similar soil.

(*iii*) *Water Content.* The following figures show the specific heats of some common soil constituents :—

Water	1·00	Clay	0·22
Gravel	0·21	Calcium carbonate	0·20
Sand	0·19	Ferric oxide	0·17

The important fact shown by the figures is that water requires about five times as much heat as the same weight of dry matter of the soil in order that its temperature may be raised by the same amount. Under otherwise equal conditions a dry soil will reach a higher temperature than a wet soil because the temperature of the water in the soil rises to a less extent than that of the dry matter in response to the same amount of heating.

A further difference arises between a wet and a dry soil. The evaporation of water from the wet soil requires the provision of heat, which heat is taken from the immediate surroundings (the soil) whose temperature is thereby reduced.

CHAPTER X

THE ABSORPTIVE PROPERTIES OF SOILS

When soils are brought into contact with solutions reactions take place between the soil and the solution which generally involve the withdrawal of some part of the solute from the solution. These reactions are of great theoretical and practical importance.

In the reactions between soils and electrolytes, the outstanding experimental facts are—

1. Soils can partially remove any cation from solution *no matter whether solutions of neutral salts or hydroxides* are used.

2. When a soil removes cations from salt solutions certain other cations leave the soil and go into solution.

3. Soils can remove only *some* anions from solutions. The PO_4 ion is perhaps the most important of those *which are partially withdrawn from solution.* The Cl, SO_4, and NO_3 ions are not removed from solution.

Drainage Water. These facts primarily determine the composition of the soil solution (p. 127) and of drainage water. The chief anions in drainage water are those of nitrates, sulphates and chlorides which are not absorbed. Phosphate ions appear in only trifling amounts, being precipitated in the soil colloids as sparingly soluble phosphate. The particular cations which are preponderant in drainage water are determined by the amounts present in the soil and their ease of replacement. Calcium is normally present

in soils in greatest amount (p. 94), is fairly readily replaced, particularly by the hydrogen ions of carbonic acid in the soil water, and appears in relatively large quantities in the drainage.

Not many direct inquiries into the composition of

TABLE 10

DRAINAGE TANK EXPERIMENTS (Hendrick)

Materials Applied and Recovered, stated as Pounds per Acre

First Period

	I	II		III		IV	
Tank.	Un-manured.	Sulphate of Ammonia.		Super-phosphate.		Muriate of Potash.	
	Recovered.	Applied.	Recovered.	Applied.	Recovered.	Applied.	Recovered.
Nitrogen as ammonia	1	119	$\frac{3}{4}$	—	$\frac{1}{2}$	—	$\frac{3}{4}$
Nitrogen as nitrate .	$122\frac{1}{4}$	—	$245\frac{3}{4}$	—	$133\frac{1}{4}$	—	$142\frac{1}{2}$
Phosphoric acid . .	1	—	1	$160\frac{1}{4}$	1	—	1
Sulphuric acid . .	67	339	321	359	$340\frac{1}{4}$	$1\frac{1}{2}$	$109\frac{1}{2}$
Chlorine . .	$41\frac{1}{4}$	—	42	1	42	273	317
Lime . .	167	—	$415\frac{1}{4}$	304	301	1	345
Magnesia .	$41\frac{1}{2}$	—	$200\frac{1}{2}$	$9\frac{3}{4}$	$89\frac{1}{2}$	$1\frac{1}{2}$	$84\frac{3}{4}$
Potash . .	$10\frac{1}{4}$	—	14	—	10	272	$13\frac{1}{4}$
Soda . .	$102\frac{1}{4}$	—	136	—	$175\frac{1}{2}$	—	152

drainage water have been made in this country. The recent work of Hendrick with the Craibstone drain gauges near Aberdeen and the longer established work with the drain gauges of Broadbalk field at Rothamsted are the two chief British sources of information. Table 10 is quoted from Hendrick's first results with

four differently treated tanks, and should be noted in conjunction with the foregoing remarks.

At Rothamsted the total concentration of the drainage water appears to vary between about 250 and 400 parts per million. The higher concentrations obtain with the more heavily manured plots. Its composition shows the same general features—relatively high nitrate, sulphate, and chloride figures compared with those for phosphate, and relatively high calcium figures compared with those for potash.

The Absorption of Anions

The removal of certain anions such as phosphate ion from solutions, is a consequence of the exchange of bases between the soil and the solution. Whenever the cations passing from the soil into solution form insoluble salts with the anion present, that salt is, of course, precipitated with a consequent removal of the anion from the solution. When cations, going into solution, do not form insoluble salts with the anion present, that anion is never removed.

Base Exchange

When soils react with salt solutions, the exchange of bases between the soil and the solution is very rapid, and for all practical purposes may be regarded as instantaneous. This indicates that the active cations held by the soil are held on the surface of the particles. Soil chemists visualize the position in some such way as is diagrammatically indicated in Fig. 6. The soil particle with its cations is regarded as a kind of salt in which the colloidal bodies of the particle constitute the anion.

After one treatment of a soil with a salt solution,

an equilibrium is established in which the various bases are distributed between the soil and the solution. If the solution is filtered off, and the treatment with salt solution repeated several times, practically the whole of the bases originally present in the soil will be replaced by the cations of the salt used. In this way soils may be prepared containing any desired cation. One may prepare sodium soils, calcium soils, hydrogen soils, and so forth.

There are considerable alterations in the properties of the soil incurred by changing the cation. A sodium soil, for example, tends to be very sticky, to have its particles more highly dispersed, and to remain for a long time suspended in water. A calcium soil, on the other hand, has these sticky properties reduced to a minimum, the particles are well aggregated together, and settle out from aqueous suspensions relatively quickly.

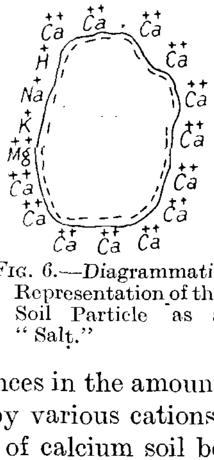


FIG. 6.—*Diagrammatic Representation of the Soil Particle as a "Salt."*

There are also considerable differences in the amount of soil base which can be replaced by various cations. If, for example, two equal portions of calcium soil be treated with equivalent amounts of potassium chloride and sodium chloride, it will be found that the potassium will have replaced more calcium and have been absorbed itself to a greater extent than the sodium. In both cases, repeated treatment will replace all the calcium with potassium or sodium, but the potassium will effect the replacement more quickly than the sodium. The following ions are arranged in descending order of their replacing power :—

$$H > K > NH_4 > Na > Li$$

There is a connection between the replacing power of a cation and the properties of the soil containing that cation. Cations which have the lowest replacing power tend to produce in soils a stickiness and a high degree of dispersion, whereas cations which have the greatest replacing power tend to produce opposite properties.

It has been pointed out by Wiegner that those cations which have the greatest replacing power are least hydrated, i.e. have a relatively small number of water molecules combined with them, whereas those cations which have the least replacing power and produce the more sticky complexes, are those which are most heavily hydrated. The heavily hydrated cations can presumably get into less intimate association with the soil colloids than those which are less encumbered by attached water molecules.

It is customary, as in dealing with many reactions, to speak as if the equilibrium between soil bases and solution bases was a static equilibrium. There is little doubt, however, that a dynamic equilibrium obtains between the soil and the solution in contact with it.

Saturation. The exchangeable cations held by natural soils are mainly confined to calcium, magnesium, sodium and potassium, and in most approximately neutral soils the calcium comprises about 80 per cent. of these. In "alkali" soils (p. 40) sodium is usually present in greatest amount and is accompanied by potassium and sometimes magnesium and calcium. When the whole of the absorptive power of the soil is satisfied with metallic cations the soil is said to be *saturated.* When hydrogen ions are among the cations the soil is *unsaturated.*

In some of the older literature the word "unsaturated" is applied to acid soils, but that is not usual

now. It is important to understand the difference between an *unsaturated* soil and an *acid* soil. A fully saturated soil along with water is an alkaline system quite comparable to the salt of a strong base and a weak acid, e.g. sodium phosphate. The system will only be neutral when a definite amount of the cations are replaced by hydrogen ion, just as phosphoric acid will be exactly neutralized by much less than its chemical equivalent of sodium hydroxide.

When salts react with unsaturated soils hydrogen ions naturally participate in the exchange phenomena. They will not, however, exceed the hydroxyl ions in solution and incur acidity unless either the soil or the salt is itself acid. When *neutral* salt solutions are applied to *acid* soils the solutions become acid to a much greater extent than when pure water is applied, because of the ionic exchange. In consequence of this acidity, certain secondary effects ensue, notably the slow dissolution of aluminium and smaller quantities of iron, and occasionally manganese. This aluminium is sometimes referred to as "exchangeable" aluminium, it being assumed that aluminium ions exist on the surface of the soil particle in the same way as calcium, etc. There is a possibility that aluminium ions do exist in this kind of way under certain conditions, but in the neutral salt action on acid soils, the bulk of the aluminium, etc., which comes into solution, does so slowly and gradually. When a neutral salt solution acts on an acid soil, the exchange between the cation of the salt and the calcium, hydrogen, and other cations of the soil takes place immediately, but it may be an appreciable time before the aluminium and iron can be detected in the solution, and their passage from the soil to the solution will continue for days. This indicates that the aluminium comes into solu-

tion in consequence of the action of the acid on the soil.

Many soils contain what is generally called a "reserve" of calcium carbonate. These are usually soils in which the absorptive power of the soil is satisfied with calcium and perhaps small amounts of magnesium, sodium and potassium, and which in addition contain particles of calcium carbonate. It is also possible for particles of calcium carbonate to remain mixed with an unsaturated soil in which hydrogen ions, among others, are absorbed on the particle surface. When, however, the calcium carbonate and the unsaturated soil particles are brought into intimate contact in the presence of moisture, as for example when the soil is moistened and gently rubbed up in a mortar, the calcium carbonate reacts with the unsaturated soil with the formation of carbonic acid, the calcium replacing the hydrogen. In the field, however, unsaturated soil particles and calcium carbonate can co-exist, sometimes for years.

One may visualize four different conditions of the soil crumb, so far as their reactive cations are concerned :—

1. A soil may be saturated with calcium, etc., and have in addition a reserve of calcium carbonate. Such a soil is alkaline.

2. A soil may be saturated and have no reserve of *calcium carbonate. Such a soil is alkaline.*

3. A soil may be unsaturated. Such a soil may be alkaline, neutral, or acid according to the ratio of hydrogen ions to other cations.

4. A soil may be unsaturated and yet have a reserve of calcium carbonate.

These four different states of affairs are illustrated diagrammatically in Fig. 7.

These four conditions of the soil crumb are differentiated in respect of their surface cations. Beneath the

surface or on the surfaces of particles within the crumb, undissociated complexes with other cations may exist. Soil aggregates which are saturated with metallic cations may—and in this country generally

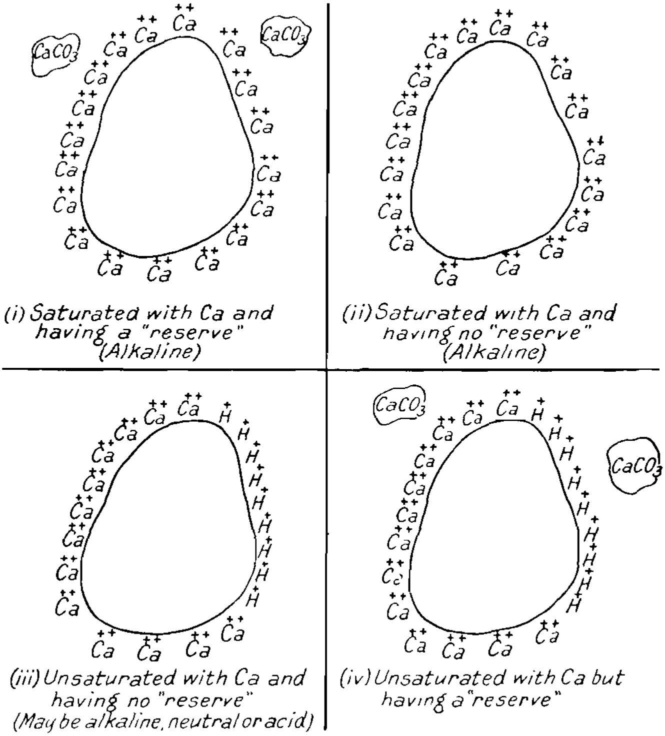


FIG. 7.—The Four Different States of Cation Saturation.

do in all probability—have potential hydrogen ions within them. When subsoils[1] in this condition are gently heated, the surface gel is shrivelled and the inner hydrogen complex becomes the surface giving

[1] The presence of organic matter introduces complications in the case of surface soils.

unsaturated and even acid properties to the subsoil. So far as present knowledge goes therefore, the complete mental picture of a soil crumb is something like the diagrammatic illustration in Fig. 8.

It is doubtful whether under field conditions, the whole of the calcium is ever replaced by hydrogen. By treating the soil, however, with slightly stronger

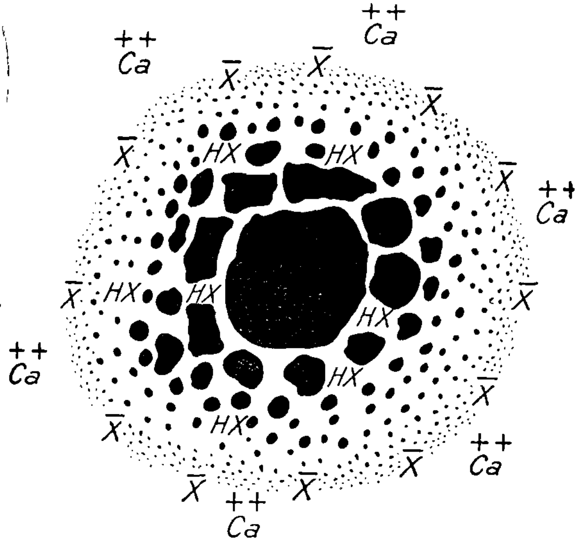


Fig. 8.—Diagrammatic Representation of a Saturated Soil Crumb showing undissociated Colloidal Acids (HX) between the Particles within the crumb and Dissociated Calcium "Salt" at the Surface.

and more concentrated acid than normally occurs in the soil, it is possible, quite easily, to remove all the calcium and replace it with hydrogen. This complete change can be easily effected by cold dilute acid.

Soils flooded with Sea Water. In some districts near the coast, land is sometimes flooded with sea water. When this happens base exchange ensues

between the cations (chiefly sodium) in the sea water, and the calcium in the soil, so that a sodium soil is formed. When the land is very heavy the consequence of this may be very serious in view of the stickiness of sodium clay, which asserts itself when the surplus salt (which has a flocculating effect) has disappeared. Such land can usually only be reclaimed by replacing the sodium again with calcium.

An interesting instance of base exchange phenomena is found in the land reclamation work which has been going on for many centuries on the North Coast of Holland. The silt deposited by the sea is allowed to accumulate until there is a sufficient area of it to justify the building of a dyke to prevent further incursions of the sea. The silt which is deposited, having been in contact with sea water, is essentially a sodium complex, but in addition, there is a large amount of calcium carbonate particles. Within a year or so of the dyking-in the surplus sea salt is almost entirely removed in the drainage water, and the calcium carbonate proceeds to react with the sodium clay, gradually bringing about the formation of calcium clay.

The Lime Status of Soils

The development of knowledge of the constitution of the soil, and of the phenomena of base exchange, has brought about important developments in our outlook on the lime question. The practical importance of lime or calcium carbonate in maintaining and improving soil fertility was known centuries before men had knowledge of the chemistry involved. When chemists first turned their attention to the matter, they examined soils in respect of their " lime " content, by estimating the free calcium carbonate present.

Soils which contained no free calcium carbonate were regarded as being "deficient in lime." Even to the present day one frequently finds in the agricultural and general Press, the advice given that soils which do not effervesce with acid should be limed. Ten or fifteen years ago it began to be clear that more important than absence of free calcium carbonate was the deficiency of *absorbed* calcium, and efforts were made to try and get some measure of this. These efforts resulted in the introduction of a very large number of methods for determining the "lime requirement" of soils. The methods suggested were based on one of three ideas.

(i) The soil is made to react with calcium carbonate, and the carbon dioxide evolved is taken as a measure of the calcium carbonate decomposed, which in turn is dependent upon the amount of unsaturation.

(ii) The soil is made to react with a neutral salt, and the acidity of the resulting solution is measured by titration (p. 95).

(iii) The soil is made to react with calcium hydroxide or calcium bicarbonate, and the reduction of the alkalinity of the solution is measured by titration.

The Hutchinson-McLennan method, which is most commonly used in this country, involved the reaction of the soil with calcium bicarbonate and the determination of the reduction of the alkalinity of the solution.

It was soon recognized that all these methods were arbitrary. When the soil reacts with the calcium carbonate, the extent of the reaction and the amount of carbon dioxide evolved is very largely dependent upon the temperature. When the soil reacts with a neutral salt solution, the acidity developed depends upon the relative amounts of salt and solution, and probably other factors. When the soil reacts with

free base, the amount absorbed again varies with the concentration of the solution and the relative amounts of soil and base. Nevertheless, much useful work was done by the development of these methods, both on the academic side, in furthering our knowledge of the problems involved, and on the practical side by giving farmers some information about the amount of lime or chalk which they ought to apply to particular areas. This information is very much more useful to the farmer than a knowledge of the amount of calcium carbonate held in reserve, which was all a chemist could tell him before the lime requirement methods were introduced. In order that any one of these methods may be of practical use, it is necessary for the results obtained by them to be considered along with practical experience of the soils and conditions involved. One of the most notable achievements in this connection was the way in which Hanley was able to correlate the results obtained by the Hutchinson-McLennan method with the economic requirements of various Yorkshire soils.

The manifest limitations of the lime requirement method led to another suggestion which arose from the work of Hissink in Holland, and Gedroiz in Russia. It was suggested that instead of trying to measure the amount of lime deficiency in an unsaturated soil, it might be easier and more useful to measure its complement, namely the calcium which is present and absorbed by the soil. Simultaneously with this suggestion there arose, both in Hissink's laboratory and in this country, the suggestion that the ratio of the lime deficiency to the absorbed lime present, or the expression of one of these as a percentage of the total absorptive power, might be useful. For example, it was noticed during Hanley's lime requirement work

in Yorkshire, that a particular lime requirement was sometimes associated with very serious crop failures, and other indications of a lack of lime, while other soils having the same lime requirement, showed no serious urgency for the addition of lime. It became clear, too, that a given lime requirement, say 0·05 per cent. Ca, might be very serious on a light soil, but not on a heavy soil. Now a light soil has a very much lower absorbing power than an equal weight of a heavy soil and the same calcium deficiency may therefore be a very small percentage of the total absorbing power, and insignificant compared with the absorbed lime present in a heavy soil, while it might be a very high percentage of the total absorptive power of a light soil, and might even be greater than the amount of absorbed lime present. Fig. 9 will make this clear.

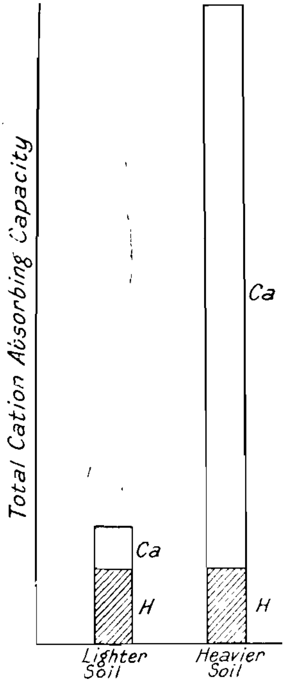


FIG. 9.—Diagrammatic Representation of two soils with the same *absolute deficiency* of Ca but with different Degrees of Unsaturation.

In Yorkshire, in addition to measuring the lime requirement, the practice was adopted of extracting another portion of the soil with dilute acid, and so removing all the absorbed lime and satisfying the absorptive power completely with hydrogen. Thereafter another lime requirement determination was made on the extracted soil, so measuring what

might be called the "maximum lime requirement." The difference between the lime requirement and the maximum lime requirement is, qualitatively, a measure of the absorbed lime. Reference to Table 11 will show that (i) the difference between the maximum and the actual lime requirement, expressed as a percentage of the maximum lime requirement, and (ii) the replaceable calcium, are better guides to field requirements than the lime requirement itself. Hissink calls the total quantity of cations the soil can absorb T, the quantity of metallic ions actually held S, the quantity of hydrogen ions held being T–S. The "degree of saturation," V, is $\frac{100\ S}{T}$. From Hissink's work it

TABLE 11

LIME REQUIREMENT, MAXIMUM LIME REQUIREMENT AND REPLACEABLE CA OF SOME YORKSHIRE SOILS

Soil No.	Response to Lime in Field.	(*a*) Replaceable Ca.	(*b*) Lime Requirement.	(*c*) Maximum Lime Requirement.	(*c–b*).	(*c–b*) expressed as a percentage of (*c*).
		Per Cent. Ca.	Per Cent. Ca.	Per Cent. Ca.		Per Cent.
1	Do not respond	0·556	0·038	0·336	0·298	88·69
2		0·334	—	0·225	0·225	100·00
3		0·305	—	0·211	0·211	100·00
4		0·208	0·018	0·139	0·121	87·06
5		0·208	0·030	0·106	0·076	71·69
6		0·183	0·110	0·200	0·090	45·00
7	Respond	0·155	0·112	0·188	0·076	40·42
8		0·099	0·093	0·144	0·051	35·41
9		0·094	0·105	0·152	0·047	30·92
10		0·064	0·141	0·157	0·016	10·19
11		0·047	0·173	0·195	0·022	11·28
12		0·039	0·085	0·105	0·020	19·04

December, 1924.

would appear that no need arises, generally speaking, for the application of lime to agricultural soils unless the degree of saturation is much less than 40 per cent. to 50 per cent. (p. 96).

Soil Sourness and its Causes. "Sourness" is essentially a practical term. It is sometimes used by agriculturists in relation to the stickiness of a heavy soil, but more frequently to describe a state of infertility which is corrected by the application of lime or chalk. This condition of infertility is characterized by a failure of certain crops. Barley is one of the most susceptible crops and fails on sour land at about the eighth or ninth week in a very characteristic way. Sugar beet and mangolds are also very susceptible. Wheat is affected, but not usually in such a marked way. Oats, potatoes and rye are not as a rule seriously affected by sourness. Legumes are sometimes seriously affected. There is also associated with sour land a fairly characteristic weed flora, arising from the reduced competition which the weeds meet with from a failing crop. Spurrey and Mayweed frequently occur on sour arable land, and Bent Grass, Sorrel and Woodrush are characteristic weeds on sour grassland. The disease generally known as "finger and toe" or "club root" in cruciferous crops also appears to be associated with sour conditions.

It was fairly apparent long ago that these sour soils are always acid, or in more recent terminology, have a very high degree of unsaturation. The use of indicators still affords a rapid means of identifying sour soils. The neutral salt action can also be used in view of the fact that the solution only becomes acid and takes aluminium and iron into solution when the degree of unsaturation exceeds a certain amount. If potassiun thiocyanate is used as a neutral salt, the red colour

produced by the iron which comes into solution from acid soils affords a fairly delicate test.

In recent years much attention has been given to the relationship of crop yield to the hydrogen-ion concentration of the soil. The acidity of soils generally varies between $p_H = 3 \cdot 5 - 4$ in the most acid soil, and $p_H = 9 - 10$ in the most alkaline. The p_H of any one soil tends to remain fairly constant since the buffering effects of the silicates, humates, phosphates, etc., reduce its susceptibility to minor influences. Only relatively drastic treatment such as the addition of dressings of lime or calcium carbonate, and the extensive and continued use of ammonium sulphate [1] will bring about any great changes. It is manifestly important, therefore, to know how various crops thrive in soils of particular hydrogen-ion concentrations and what crops thrive best at any particular p_H value. Probably the most exhaustive investigation is that made in Sweden by Arrhenius, who grew a large number of farm crops in soils of varying p_H values, and was able to show that there is for any particular crop a p_H range over which, under the conditions of the experiment, the particular crop thrives best. The following are a few of Arrhenius' results:

Crop.	p_H range.
Wheat	6·5–7·5
Sugar-beet	7·0–7·5
Barley	7·0–7·5
Turnips	5·8–6·8
Rye	5·0–6·0
Swedes	4·9–5·5 [2]
Potatoes	4·8–5·7

[1] In consequence of nitrification, the addition of ammonium sulphate is ultimately equivalent to the addition of nitric and sulphuric acids.

[2] Agricultural experience in England would probably regard a more alkaline condition than this as more suitable for swedes.

It must be understood that these are the findings of one set of experiments, and the results are not of rigorous and universal application. Under different conditions of climate, soil texture, and so forth, the results of such experiments may well be appreciably different. However, the empirical value of such information as this is very considerable in the district in which it is obtained, since if it is not possible economically to alter the soil reaction by liming, it is possible as the next best thing, to grow only those crops which are most suitable to the soil as it is. Liming an acid soil, however, has the great advantage of admitting a larger number of crops to be grown, for most of those crops which will withstand sour conditions will thrive on an alkaline soil. The potato crop is a notable exception, but the deleterious effect of lime upon potatoes is found more in the development of common scab than in the actual depression of yield. Indeed, the yield of potatoes may sometimes be slightly increased by liming.

The precise cause of the crop failures which characterize sourness has, in recent years, given rise to much discussion. There are three factors which have figured prominently in this discussion, namely :—

(*a*) Toxicity of acid.

(*b*) Toxicity of aluminium salts.

(*c*) The effect of a low ratio of calcium to other cations.

It was at one time tacitly, but quite plausibly, assumed that since sour soils are acid and the sour condition is corrected by the addition of lime, that the acidity of the soil is a direct cause of the crop failures. This assumption was, however, not strictly logical, for two factors which go hand in hand are not necessarily cause and effect. A number of observations

raised some doubt as to whether the crop failures which are symptomatic of sourness are due to the direct poisoning of the plants by acids. Hoagland in California reported the existence of soils which were decidedly acid and yet which showed none of the symptoms of sourness, and which gave no appreciable response to the addition of lime. He also contended that barley could be grown in water culture solutions at a hydrogen-ion concentration quite as great as that found in the most acid soils. Other observations suggested that aluminium ions were active in acid soils and that they, rather than the hydrogen ions, were responsible for the damage.

One of the most notable experiments which threw suspicion upon aluminium ions was carried out by Hartwell and Pember in the United States. They arranged a series of barley cultures and a parallel series of rye cultures, and increased the acidity of the culture solution from one end of the series to the other by adding increasing doses of sulphuric acid. They found that the same minimum amount of acid which depressed the growth of barley had a similar effect upon rye. This was quite contrary to the behaviour of barley and rye in sour soils, for barley is one of the most susceptible crops, and rye one of the most resistant. They repeated the experiment, using aluminium sulphate in place of sulphuric acid, and then found that a much higher concentration of aluminium sulphate was required to impair the growth of rye than to impair the growth of barley.

The relative effects of hydrogen ions and aluminium ions in the soil are still very much disputed. It has been argued that since the titration curve of aluminium salt and an alkali shows that aluminium ions cannot exist in solution at a hydrogen-ion concentration less

than that corresponding to $p_H = 4$, they cannot exist in any but the most acid soils. It does not follow, however, that the hydrogen-ion concentration at which aluminium is precipitated *in vitro* is any clue to what happens under soil conditions where organic matter and other factors have important effects. It has also been very much argued that practically no aluminium is found in the water extract of most sour soils, but it must be remembered that very little of any of the active soil cations are found in an aqueous extract.

The condition of sourness is in some way consequential upon the partial replacement of calcium ions by hydrogen ions. Calcium ions are more readily replaced than potassium and sodium ions. In sour soils, therefore, the ratio of calcium to potassium and sodium tends to be low. The low content of active calcium, or the low ratio of calcium to the other cations, has been indicated as a contributory cause of sourness. Pearsall has shown that *calluna* and *nardus* (both of which are characteristic of sour conditions) grow in the Lake District on stream gravels where the water is practically neutral but has a low ratio of calcium and magnesium to potassium and sodium. Priestley and his collaborators have shown that peat plants release large amounts of fats in their metabolism, and that a high proportion of calcium is detrimental to their growth in so far as insoluble calcium soaps are formed by reaction with the fatty substances bringing about a variety of inimical conditions.

The student will realize the possibilities of great complexities underlying the phenomena of sourness. As calcium is replaced in the soil, hydrogen ions become active and when the hydrogen-ion concentration is increased beyond a certain point, aluminium ions will

become active and bring about a variety of other secondary effects. Moreover, during the whole process the ratio of calcium to potassium and sodium will tend to become low. It seems futile in the present state of our knowledge, to try in any general way to assign these various factors to their place of relative importance. It seems more than likely that one factor may be predominant in some circumstances, and another in others. Sourness is itself superficially complicated, being diagnosed by crop failures, crop diseases, and the development of certain weeds, and the various soil conditions indicated above which accompany the state of sourness, may vary in their importance to each of these symptoms.

CHAPTER XI

SOIL NITROGEN

Nitrogen appears to be normally assimilated by plants in the form of nitrate. There is, however, considerable evidence to show that some plants at any rate, can take up other nitrogen compounds, particularly ammonium salts.

The effects of nitrogen on plant growth, as they are empirically observed, are fairly characteristic. Suitable nitrogen compounds tend to increase the bulk of plants, and frequently, to increase the bulk of the less valuable part of the plant. Increasing quantities of nitrogen will continue to increase the yield of straw after they have ceased to increase and even after they have depressed both the yield and quality of the grain. With root crops, the tendency is similarly towards a high ratio of leaf to root. The ripening of grain is retarded by too great a proportion of nitrogen in the medium of growth, and the liability to disease is considerably enhanced. Nitrogen starvation is characterized by a general yellowing of the leaf and stunted growth.

The amounts of nitrogen found in soils vary enormously. Soils rich in organic matter contain up to 1 per cent. or more ; and at the other extreme, infertile sands may contain less than 0·05 per cent. Normal figures for average and moderately fertile loams are from 0·10 per cent. to 0·30 per cent. The total amount present, however, is no guide to the amount available

for the plant, for the facility with which the nitrogen in its various compounds can be converted into nitrate, or some other easily assimilated combination, is the chief factor which determines the usefulness of the nitrogen. There is a variety of substances, of which leather waste is a notable example, which are sometimes suggested for application to the soil on account of their high nitrogen content, but which, although they literally enrich the soil in nitrogen, are almost without value to the plant since the nitrogen compounds are very resistant to the changes shortly to be considered.

The Natural Sources of Soil Nitrogen

1. Organic Matter. The protein and other *nitrogenous bodies in plant and other remains which* become incorporated in the soil constitute the chief natural sources of the plant's nitrogen. The oxidation of organic matter in the soil has been referred to (p. 31): the fate of the nitrogen during that oxidation is the special consideration which arises here.

In plant residues the ratio of nitrogen to carbon varies from about 1 : 40 to 1 : 25 (the narrower ratio is generally found in legumes). In soil organic matter (humus) the ratio of nitrogen to carbon is usually about 1 : 10.

The nitrogen in the more complex compounds appears during the course of decomposition, as ammonia, which, with the carbonic acid of the soil, forms ammonium carbonate. This process of *ammonification* appears to be brought about by a variety of organisms, fungi and soil bacteria probably participating. Under normal conditions the ammonium compounds are oxidized by the *nitrosomonas* bacteria and nitrites are produced which are further oxidized by the *nitro-*

bacter bacteria to nitrates. *Nitrosomonas* and *nitrobacter* appear to be specific to their particular stage of the change: *nitrosomonas* and only *nitrosomonas* can effect oxidation of ammonium compounds; *nitrobacter* and only *nitrobacter* can effect the oxidation of nitrites to nitrates.

The amount of nitrate present at any time is determined by the number and activity of the various micro-

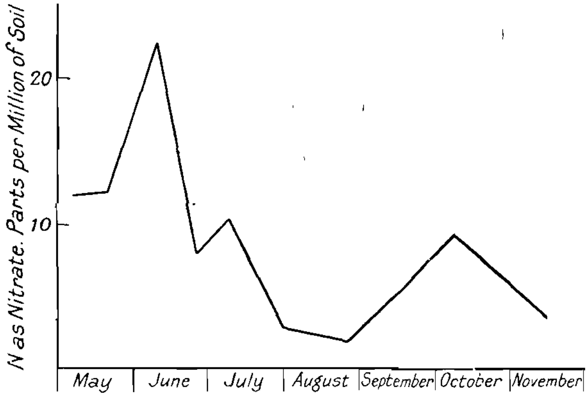


FIG. 10.—Fluctuation of Nitrate Content of a Yorkshire (Garforth) Soil. (R. Burgess, private communication.)

organisms involved. In consequence the seasonal variations, as already indicated, follow those of the carbon dioxide content (p. 83). From the Rothamsted investigations it would appear that the amount of nitrate in the soil at the spring maximum is of the order of 20 parts per million. A similar spring maximum and a similar seasonal variation is seen in Fig. 10 obtained by R. Burgess working on a Yorkshire soil.

More nitrate appears to be produced under fallow conditions than when the soil is cropped, a fact which

has an important effect upon the yield of a crop following a fallow.

2. Atmospheric Nitrogen. There exist in soils certain bacteria which are capable of taking up nitrogen from the atmosphere. This nitrogen becomes incorporated in the protein of the bodies of the organisms, and so enriches the soil in nitrogen. Some of these organisms exist in the soil quite independently of growing plants, but there is one which although it exists in the soil, only functions as a nitrogen-fixing organism when living symbiotically with legumes.

Of the nitrogen-fixing bacteria which are independent of plants, the two chief are *Clostridium Pasteurianum* and *Azotobacter Chroococcum.*

The Clostridium is a spore-forming organism which fixes nitrogen only in the absence of oxygen ; in the soil there are two bacteria associated with it whose function appears to be to remove the oxygen from the neighbourhood. Clostridium operates in soils over a wide range of soil reaction, and appears to develop in quite acid soils. Grown on culture media containing sugars it produces butyric and acetic acids among other things during the decomposition of the sugars.

Azotobacter is a non-spore-forming organism and functions aërobically. It is very susceptible to soil acidity and is rarely present in the absence of calcium carbonate. The failure of Azotobacter to develop in soils lacking in lime has been used with marked success in Denmark as a test for lime deficiency. The course of decomposition of sugars by Azotobacter is apparently different from that of Clostridium, as no butyric acid is produced. In culture media where sugars are used as a source of energy for the organisms, Azotobacter fixes four or five times as much nitrogen as Clostridium for the same weight of sugar used.

While it is known that these two bacteria exist in soils, and that in artificial media they fix nitrogen from the atmosphere, there are yet no reliable data from which any deductions can be made as to the amount of nitrogen fixed by them in the field, and to what extent the farmer is indebted to them.

Another organism, *Bacillus Radicicola*, enters leguminous plants from the soil, and is responsible for the familiar nodules on these plants. Living thus in symbiosis with its host plant, this organism fixes considerable quantities of nitrogen. Long before the organism was isolated or its function understood, it had been established by experience that legumes, notably clover, were in some way responsible for a marked improvement in succeeding corn crops. In 1874 Lawes at Rothamsted had actual analytical data to show that in one of his experiments the total barley crop following clover contained over 70 per cent. more nitrogen than the total (and smaller) barley crop which was preceded by barley. But it was not until 1888 that Hellriegel and Wilfarth demonstrated that legumes, as distinct from other natural orders, took nitrogen from the atmosphere as well as from the soil, a discovery which was shortly followed by the isolation of the organism. This discovery was of outstanding importance since it satisfactorily explained the improving effect of a clover ley upon a succeeding corn crop, and it also ended a great controversy as to whether plants did, or did not, take nitrogen from the atmosphere.

The Natural Losses of Soil Nitrogen

Apart from the removal by crops, there are a variety of ways in which nitrogen may be lost from the soil.

1. Drainage. Soils do not absorb nitrates (p. 90),

and consequently any nitrate which is formed in, or added to, the soil, will be removed as rapidly as the drainage conditions permit. On a small plot at Rothamsted which has been kept free from all vegetation, the loss of nitrogen (which in 35 years has exceeded 1,000 lb. per acre) from the top 9 inches, is *practically* the same as the nitrogen which has appeared in the drainage water as nitrate. Rothamsted also provides another striking illustration of the removal of nitrate in drainage water. Among the continuous wheat plots in *Broadbalk field*, there is one which has received no manure since the inception of the experiment in 1843, and which, for many years now, has given an average annual yield of 12–13 bushels of grain. In Agdell field there is an unmanured plot which grows wheat in alternate years, and is bare fallowed in the intervening years. The average yield of wheat in those alternate years in which the plot is cropped, is approximately 17 bushels. The higher yield of wheat following fallow when compared with wheat following wheat, is attributed to the nitrate produced from the period of fallow, and it is interesting and important to note that in wet seasons when nitrate is leached, the yield of wheat following fallow is much below the average, and only slightly greater than the yield of wheat following wheat. In abnormally dry seasons the difference between the yield of wheat following fallow, and of wheat following wheat, is most marked.

2. The Loss of Free Nitrogen. When nitrogenous organic matter decomposes under certain conditions there is an evolution of gaseous nitrogen. It has been known for some time to take place in sewage beds, and was demonstrated by Russell and Richards to be one of the chief sources of loss of

nitrogen from ordinary manure heaps. The chemical changes involved are still rather obscure, but appear to involve processes of oxidation and reduction. Russell and Richards' work made it clear that this loss ensues when aërobic and anaërobic conditions co-exist. These are the conditions which obtain in an ordinary manure heap, there being an exclusion of air from certain parts, and a circulation of air between those parts. These are also the conditions which obtain in a normal soil well provided with organic matter. Very little is known about the extent and importance of this loss of nitrogen from soils, but evidence exists of its occurrence. Losses of nitrogen have been described from certain aerated Canadian soils which the meagre drainage is inadequate to explain. There has been an average annual loss of something like 125 lb. of nitrogen per acre from the farmyard manure plot which received 14 tons of manure annually, on the continuous wheat field at Rothamsted. This high figure, and the fact that the drain from this plot scarcely ever runs, indicates the possibility of loss of gaseous nitrogen in some such way as takes place in sewage beds and manure heaps.

3. Denitrification. There is another possibility (which has no connection whatever with that just described) of a loss of gaseous nitrogen from soils. Under *anaërobic* conditions a large number of soil organisms are capable of decomposing the soil nitrate to obtain the oxygen which is no longer available as gas. This results in a reversal of the nitrification process and, in addition to the formation of nitrites and ammonia, brings about the formation and consequent loss of free nitrogen.

4. The Conversion of Nitrate Nitrogen to Organic Combinations. When there is a very high

proportion of non-nitrogenous organic matter and the nitrogenous matter falls below a certain percentage, the soil organisms attacking the non-nitrogenous matter, and for whom organic nitrogen is now limited, tend to take nitrogen from the nitrate, thereby bringing that nitrogen into organic combination. For this reason the application of straw, sawdust, etc., to soils, tends to reduce the amount of nitrate present. This of course, is not strictly a loss of nitrogen, but it involves a temporary reduction in the amount which is available to the plant.

The principal nitrogen changes in the soil may be summarized as follows :—

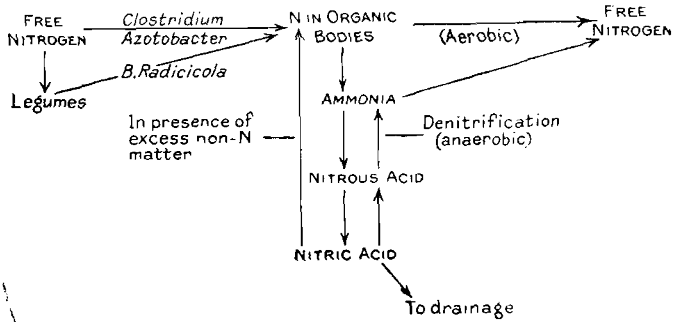


FIG. 11.

Partial Sterilization. Farming experience long ago discovered that crop growth is often considerably enhanced in places where hedge trimmings, etc., have been burned. Attempts were subsequently made to explain this as the effect of the potash which remained after burning such things, but the frequently remarkable increase in the bulk of the crop was rather at variance with the usual effects of potash. Moreover, similar results were obtained in many experiments which involved heating of the soil or the use of anti-

septics, and in which additions of potash did not arise. For example, Seton and Stewart, in experiments designed to ascertain whether common scab in potatoes was a mechanical or biological effect, incidentally noticed, but were unable to explain, a much bigger yield of potatoes in soils which had been sterilized with formalin, than in the unsterilized soil. In one experiment they obtained nearly three times the yield of potatoes as a consequence of treatment of the soil with formalin.

Systematic investigation of this matter was initiated by Russell. Russell and Darbishire investigated in a long series of experiments the effect of heat and of antiseptics upon crop yield. With non-leguminous crops they obtained increases varying from 50 per cent. to 350 per cent. as a consequence of heating the soil to a temperature of 90°–95° C. By using various volatile antiseptics they also obtained considerable increases in yield. With legumes, however, there was generally no increase consequent upon the treatment. The fact that antiseptics as well as heat have this effect, and the fact that the effect is, generally speaking, not apparent in legumes (which are able to obtain nitrogen from the atmosphere), clearly indicates a biological effect connected with the nitrogen nutrition of the plant. Russell and Hutchinson in a series of classical experiments, came to the conclusion that in the soil microfauna there exist protozoa which feed upon the bacteria and set a limit to their development and their activities, and that the effect of heat and antiseptics is to destroy protozoa but only to suppress, without completely destroying, the bacteria. After this initial suppression, the bacteria are able to develop unhampered by their former enemy, with a consequent increase in the production of nitrate. The Rothamsted experi-

ments have shown that after the partial sterilization treatment there is a reduction in the bacterial numbers followed in a few days by an increase which far exceeds the original numbers, and that this increase in bacterial numbers is accompanied by a larger production of ammonia or nitrate, or both. Moreover, a long series of daily counts at Rothamsted shows that whenever the number of protozoa in the soil increases, the number of bacteria is reduced, and that as the protozoa diminish, so the bacterial numbers increase.

It is possible that other effects in addition to the extinction of the protozoa play a part in the results which follow partial sterilization, at any rate by heat treatment. The effect of heating soils involves a number of physical and chemical changes (see p. 64), which render a number of soil constituents more accessible to the plant, and these effects may also be of some significance.

CHAPTER XII

THE MINERAL PLANT FOOD IN SOILS

Phosphorus. The effects of improving a meagre supply of phosphorus and making it adequate are very different from those which follow an increase of suitable nitrogen compounds, since the effects of phosphorus concern factors of quality rather than quantity. Suitable phosphorus compounds expedite the ripening of corn crops and they invigorate the growth of the root system. Their influence upon the roots of plants makes their adequate supply a matter of importance where obstacles to root development exist, as for example, in heavy clay soils. In lighter soils, although mechanical opposition to root penetration is not abnormally great, the stimulation of root development by phosphates is still very desirable when the water table is low, or in periods of drought and in areas of low rainfall, since the greater root range involves greater chances of drawing upon adequate water supplies.

The amount of phosphorus present in soils varies very much; 0·15 per cent. indicates the order of the amount of P_2O_5 commonly found in average loams. Some chalk soils, as is to be expected from their origin, contain higher amounts (0·2–0·3 per cent.); in very infertile areas the percentage may fall to something in the third decimal place.

Phosphorus normally exists in the soil in some form of calcium phosphate deposited in the soil colloids. When the ratio of calcium to phosphoric acid becomes low, other bases, notably the weak bases iron and alumina, may enter into combination with the phosphoric acid. The lower solubility of the phosphates of iron and aluminium has led to the assumption that the phosphorus in such compounds is of less use to the plant. Direct evidence of this is however lacking, since when the lime status of the soil becomes low and the possibility of these other phosphates being formed arises, other conditions are set up (p. 108) which establish a state of infertility. The presence of iron and aluminium phosphates in the soil necessitates acidity and a low lime status. The difficulty of making a direct and simple experimental investigation of the effects of iron and aluminium phosphates in the soil as compared with those of calcium phosphate is one illustration of the fundamental difficulty of all such soil work, namely that it is impossible to alter one soil condition and keep all the others constant. In sand cultures iron and aluminium phosphates have been found to compare very favourably with calcium phosphate as a source of phosphorus for the plant.

Phosphate is not leached from the soil to any very great extent and the danger of loss in drainage which is so great in connection with the nitrogen nutrition of plants does not seriously arise here.

Potassium. As with phosphorus, nitrogen, and other nutritional elements, knowledge of the effects of potassium compounds upon plants arises from empirical observation more than from any understanding of the physiological processes involved. Like phosphorus, and indeed all the mineral elements of plant food, the effects of potassium are more intimately connected

with factors of quality than of quantity. No plant will grow, of course, in the absence of any essential element, but the insufficient supply of these elements has a less general effect upon the bulk of a plant than in the case of nitrogen.

Potassium is in some way intimately connected with starch formation, and appears to increase the velocity of the photosynthetic processes. Improving the potassium supply frequently brings about a small increase in the leaf area of plants, but this increase is trivial compared with the increase in the amount of carbohydrate formed. What may be roughly described as the "stamina" of a plant, its power to resist disease and insect attacks, is only maintained when potassium supplies are adequate. The effects of potash starvation are well seen on the classical Rothamsted plots. Cereal leaves assume a characteristic dark green, and tend to die at the tips; grain is frequently stunted and sometimes sterile. Unlike phosphorus compounds, potassium compounds delay the maturation of plants. Arising from the survey of Sussex, Surrey and Kent, Hall and Russell point out that potassium is more useful under a low rainfall, which they attribute to its effect in delaying ripening and so counteracting the opposite effect of dry climatic conditions. Heavy clay soils may contain 1 per cent. or more of K_2O, and in light soils the figure may fall to 0·1 per cent. or less. Hall and Russell's data show that roughly speaking, the percentage of K_2O is about one-tenth that of the aluminium, which in turn is about one-third that of the clay.

Other Mineral Elements. The plant contains a large variety of elements other than those which are commonly applied as fertilizers. *Silicon* is an invariable constituent of plants grown in soils, and investiga-

tions at Rothamsted and elsewhere show that soluble silicate has an effect in cases of phosphate deficiency. Either the silicon in some way functions in the place of phosphorus or, what is more probable, the silicate by some obscure means, facilitates the uptake of phosphorus compounds. The significance of *boron* in connection with leguminous plants has been mentioned on page 12. In the course of this arresting research at Rothamsted it has been shown that boron is necessary for the effective symbiosis of the *Bacillus Radicicola* and the plant. *Sodium* is a universal constituent of soil-grown plants and, directly or indirectly, can replace potassium to a certain extent. On the continuous mangold plots at Rothamsted the effect of sodium nitrate alone is much greater than the effect of ammonium salts alone, and is about equal to the effect of ammonium salts together with potassium salts. Moreover, the addition of potassium salts to the plots receiving sodium nitrate does not effect any appreciable increase in yield. It is suggested that this is a consequence of a base exchange in which sodium replaces potassium, bringing it into solution and thereby rendering it more available to the plant. It is also possible that sodium can perform some of the duties of potassium in the processes of plant physiology, and there are other complicated possibilities arising from the effect of sodium salts upon the permeability of plant membranes. *Iron* in small quantities is in some way or other involved in the formation of chlorophyll and a state of chlorosis in which the leaves are yellow or even white may obtain where iron is not available, and may be rectified in some instances by the addition of iron salts. The lack of iron is undoubtedly one factor in the incidence of chlorosis, but the phenomenon is probably more complicated

than that. Although iron is required for the making of chlorophyll, it does not appear to enter into the composition of chlorophyll. *Magnesium* is also essential for the formation of chlorophyll and is a constituent of it, the ash of chlorophyll being magnesium oxide. *Copper* normally occurs in soil-grown plants, and may have a marked effect upon the species which are developed on grassland. Copper telegraph wires running across grassland sometimes have a curious effect upon the herbage immediately under them. The difference in colour between the area under the wires and the outside area is sometimes apparent from a long distance. Clover appears in flower under the wires when there is no sign of a clover flower elsewhere, and where daisies are abundant in the field they are sometimes not to be seen in the strip under the wires. Other plants are affected and the strip under the wires develops bare patches in the course of time. It must be remembered that rain water falling from the wires falls upon the leaves and vegetative parts, and may possibly produce effects in that way quite different from those which follow the intake of copper by the root hairs. *Aluminium, Manganese, Chlorine, Sulphur, Titanium,* are frequent constituents of plants, and some at least of them are essential constituents.

The Availability of Mineral Plant Food

It has long been known that the total quantities of phosphorus and potassium (and presumably other mineral elements) existing in the soil, bear little relationship to the response of crops to further additions. Two soils, similarly situated, may contain different amounts of P_2O_5 and K_2O, and the crops growing in the soil containing the larger amounts may respond to further additions, while those growing in what

appears to be the poorer soil may be quite satisfactory and show no response to further additions. In two fields on the Leeds University Farm, the respective amounts of P_2O_5 were found by Ingle to be 0·15 per cent. and 0·12 per cent., although root crops responded to the phosphatic fertilizers applied to the first and not to the second.

The impossibility of drawing straightforward conclusions in a simple way about the mineral requirements of soil from analytical data was realized long ago, and Daubeny at Oxford suggested that some part of the mineral plant food was *active* and another part *dormant.* The soil containing the greater total amount might have a small percentage of active plant food, while a soil containing a lesser amount might have a larger amount in the active form. It is not necessary to suppose, and it is hardly likely to be true, that the phosphate, for example, in a soil exists in two distinct chemical and physical forms, one of which can be used by the plant, and the other of which cannot. In one soil the phosphate, etc., may be in a position to enter the plant readily and in another soil conditions may deter its adequately rapid uptake. The terms " active " and " dormant " have become replaced by *available* and *unavailable,* and in considering mineral plant food in soils, soil chemists are concerned not only with the total quantity but with its *availability.* A classical research into the problem of availability was carried out by Bernard Dyer at Rothamsted. At that time it was supposed that the root hairs of plants excreted organic acids which attacked the soil particles in their immediate environment and rendered phosphate, etc., soluble and more easily obtainable by the plant. On this assumption Dyer extracted the saps from the root cells of many

common agricultural plants and titrated them with alkali. On the basis of the titre he found that a 1 per cent. solution of citric acid has the same acidity as the sap of the roots of most of the common crops. Thereafter he propounded a method for extracting soils with a 1 per cent. citric acid solution and estimating the potash and phosphate dissolved. The figures obtained were very much more in accordance with the facts observed in the field. The two soils mentioned by Ingle containing respectively 0·15 per cent. and 0·12 per cent. P_2O_5 showed respectively 0·0049 per cent. and 0·0205 per cent. soluble in citric acid under the conditions of the experiment. The soil containing 25 per cent. more "total" P_2O than the other contained only about a quarter of the "available" P_2O_5. Although plant physiologists appear to have abandoned the view that organic acids are excreted by plant roots, Dyer's method is still in very general and successful use. In many laboratories citric acid has been replaced by some other acid, but extraction with dilute acid is the only means at present at our disposal of attempting to estimate the availability of phosphate.

There are other possibilities of dealing with potassium since it seems fairly clear that available potassium is entirely comprised in the replaceable potassium. Ramann used the amount of potassium replaced in the neutral salt action as a measure of the available potassium, and that method may yet be developed, although it is quite possible that even the absolute amount of replaceable potassium may have to be considered in conjunction with its ratio to other active cations.

The Intake of Soil Constituents by Plants. The Soil Solution. A proper understanding of availability is clearly dependent upon a true conception of the

mechanism whereby plant food in the soil enters the plant. This crucial problem is still a little obscure.

There appear to be three possibilities which may be briefly discussed :—

(1) Solutes *already in true solution* in the soil water diffuse into the root hair cells. (2) The plant brings soil constituents into solution by some means or other. (3) Colloids as well as true solutes enter the root hairs.

1. Among botanists and soil chemists the usual and "orthodox" views involve only the first of these possibilities. The others are not altogether denied as possibilities, but it is held that the first is the most obvious and natural assumption, and is adequate to explain the facts. The plant growing in soil is regarded as being in much the same position as the plant growing in a culture solution, except that in the soil the solution is spread over a lot of particles instead of being contained in a bottle. Whether that is the whole story or not it is clear that absorption from solution must play a prominent part in plant nutrition. Nitrate, for example, only exists in solution in the soil.

Attempts have been made to remove the soil solution from the soil and examine it separately in bulk. Two general methods have been used: (1) eliminating the solution by the application of high pressure; (2) replacing the solution by another liquid. Notable work has been done, particularly by Burd, Hoagland and others in California. Table 12 is taken from the results of Burd and Martin and will give some idea of the order of the amounts of solutes found in the water displaced from the soil. The solution is clearly very dilute, particularly in respect of potash and phosphate. The Californian work indicates, however, that such

low concentrations of phosphate, etc., are adequate to feed plants provided the amounts removed by plants *are rapidly replaced during that stage of growth in* which the particular nutrients are required. The soil particle evidently has the power of giving up phosphate and potash very rapidly to the solution around it, for if the moisture content of a soil is increased by adding pure water, the concentrations of phosphate and potash are not diminished in proportion to the amount of water added ; the soil gives up more of them in response to the addition of water. The concentration of nitrate,

TABLE 12

AVERAGE COMPOSITION OF DISPLACED SOLUTIONS FROM CROPPED (A) AND FALLOWED (B) SOILS AFTER 8 YEARS (Burd and Martin, *Soil Science*, Vol. 18).

Soils.	Moisture.	Negative Ions. Milli-Equivalents.						Positive Ions. Milli-Equivalents.				Total Ions. Milli-Equivalents
		NO_3.	HCO_3	Cl.	SO_4.	PO_4.	SiO_3.	Ca	Mg.	Na.	K.	
	Per Cent.											
A	12·6	3·72	1·84	—	12·53	0·08	1·61	10·14	7·10	1·84	0·68	39·54
B	16·3	29·56	1·02	1·44	9·66	0·07	1·48	27·88	10·99	2·77	1·61	86·49

which only exists in the solution, is naturally diminished in proportion to the amount of water added.

The other possibilities cannot however be ruled out.

2. Although plant physiologists have abandoned the old view that root cells excrete their contents into the soil, it is still possible for the root hairs to " attack " the soil particles. As the root hairs grow among soil particles, they develop a mucilaginous colloidal surface which merges with the colloids of the soil particles so that the soil and the plant become irrevocably attached, forming *one system.* The soil particles can

never be detached from the root hairs without tearing them. The root hairs do not just *dip into* the soil solution: they are united with the particles. It is therefore possible for the organic colloids and solutes of the root hairs to withdraw mineral constituents from the soil acting in the same kind of way as is described on page 42 in connection with podsolization. The uptake of iron, etc., by plants from alkaline soils and by lichens, etc., from limestones may be a consequence of this type of action. Mineral phosphates appear to have colloidal properties not unlike those of soils, and their service to the plant may very well be due in part to the union between them and the root hairs. The effect of basic slag on wild white clover, for example, may be due, not so much to the dissolution of the phosphate and its dissemination throughout the soil solution, as to the presence among the soil particles of additional and phosphatic colloidal particles with which the root hairs make their union and which they attack.

3. It is explained in Appendix A that the difference in the respective powers of diffusion of colloids and crystalloids is a matter of degree: colloids are not in general completely indiffusible. Moreover, there are some indications that bodies in the colloidal state can pass a protoplasmic membrane. The possibility that plants can take in some of the soil colloids must therefore not be rejected.

CHAPTER XIII

THE CLASSIFICATION OF SOILS

Soil chemists and agriculturists frequently speak about soil "types," and yet the definition of the various types is a matter which presents very considerable difficulty. When soils that differ in some obvious respect are considered together, it is easy to refer to "this type" and "that type," and it is possible to ascertain in what particular respect the two soils differ. Nevertheless the mapping of soils in order to show the distribution of various types has proved to be an almost overwhelming problem on account of the difficulty of finding a satisfactory criterion of a soil type which will be of general application. The fact that soils differ is obvious enough, but the attempt to classify them is by no means easy.

It must be remembered that on the basis of such properties as the agriculturist associates with fertility there is no natural classification of soils corresponding to the classification of plants and animals. It is admittedly easy to find a sandy soil and a clay soil, and discriminate between them on the basis of their texture, but in the geographical distribution of these soils there is not necessarily a sharp line of demarcation between them. Starting from a spot on a sandy soil, it may easily be possible to proceed to a spot on a heavy soil without ever being able to say where the soil ceased to be sandy and where it began to be heavy. If all the soils that have been examined in this country

were arranged in increasing order of heaviness, every stage of transition from light sands to heavy clays would be exemplified. Moreover, the soil is not usually uniform throughout its depth. For example, what appears at the surface to be a sandy soil, may have, a little below the surface, a layer of much heavier material, and the depth at which that layer occurs may vary considerably. Every degree of complication and transition is possible, and any classification on the basis of its obvious properties and those most easily associated with its crop-producing power, must be arbitrary.

It is well known as a matter of long experience that certain areas of soil are particularly suitable for certain crops and certain types of farming, and not for others. Attempts have been made to examine the soils on these areas and, by working backwards so to speak, to ascertain what are the particular properties connected with its special suitability. The pertinent properties, however, are often of a different kind. For example, there are areas of land in this country which have long been known to farmers as " wheat and bean land," and we know that the particular soil characteristic which makes these areas suitable for those crops is clay content. In the Vale of York there are areas which have come to be known as " oat, rye and potato land," but the particular soil characteristic which restricts cropping possibilities to those three crops is lime deficiency. There is no one universal characteristic underlying the suitability of a soil for a particular type of husbandry.

In spite of all the difficulties attending this matter, a good deal of useful work has been done, and the developments in recent years indicate that greater advances will be made in the future. It will be

useful, in considering this subject, to discriminate between two different points of view. Attempts have been made to classify soils and to prepare soil maps from the point of view of the industry of farming, and in order to show a correlation between soil and the agriculture associated with it. Other attempts have been made to classify soils regardless altogether of any industry connected with them, and neglecting any crops that grow upon them, except in so far as native vegetation is involved in the making of the soil. There are, therefore, what may be called the *agricultural* and *scientific* classifications which have been attempted.

The Agricultural Classification of Soils

The two important bases of classification which have been invoked in the attempts to prepare soil maps of agricultural significance, are the geological basis and the physical basis.

1. Geological Classification. In so far as the structural basis of a soil is formed from a parent rock, it would at first sight appear reasonable to suppose that different geological formations would give rise to different types of soils, and that the soil map would be largely, if not entirely, coincident with the geological map. There are certain areas in this country in which this is true to a useful extent: the classical survey of the agriculture and soils of Sussex, Surrey and Kent by Hall and Russell is an illustration of the usefulness and value of taking the geology of a district as a starting-point for mapping its soils. In a large part of Yorkshire geological boundaries are also the boundaries between different types of soil and of farming, and it is of practical value to speak of the "magnesian limestone soils," the "coal measures shale soils," the

"millstone grit soils," and so forth. On grassland it is possible in passing from the Magnesian Limestone Soil to an adjoining Coal Measures Soil to note abrupt changes in the herbage, *Brachypodium* and *Bromus spp.* giving place to *Agrostis spp.* But even in areas where the geological distribution of soils is of practical use, the relation of soil properties to geology is by no means perfect. This partly arises from the fact that two areas may be geologically the same and yet differ very much lithologically. It also arises from the fact that the same rock under different weather conditions will give rise to a different soil. So it comes about that in such districts as those named, the geological classification of soils is very useful *up to a point only,* while in other areas, e.g. North Wales, the geological classification is of less practical significance. It is abundantly clear that one cannot take the geological map as it stands and conclude that areas similarly marked on it are covered by similar soils. The Pennine district of West Yorkshire and the bog land of Central Ireland are identical on the geological map.

It is manifest that more value attaches to the drift map than to the solids map, but the drift map is limited in its usefulness because, among other things, the geologist even in making his drift map, pays no attention to the surface soil.

2. Physical Classification. A general inspection of soils, apart altogether from any scientific investigations, makes it quite obvious that soils can be grouped under three headings :—

(1) *Organic or Humus soils,* in which the organic matter is dominant and inflicts its properties upon the soil. This group includes (*a*) *peat* soils in which organic matter has accumulated in the absence of calcium

TABLE 13

EXAMPLES OF MECHANICAL ANALYSES

	1	2	3	4	5	6	7	8	9	10	11	12	13
Fine Gravel	6·78	0·43	0·47	0·50	0·42	1·51	0·67	0·77	—	1·94	6·68	1·95	—
Coarse Sand	20·40	32·00	14·13	7·63	5·25	20·60	7·30	4·92	0·56	6·49	5·06	11·93	1·67
Fine Sand	20·19	16·40	15·06	2·36	59·63	32·00	11·57	37·40	20·53	7·74	29·87	41·40	32·52
Silt	12·95	10·21	8·82	22·46	12·60	4·70	12·86	7·10	18·20	18·96	21·36	14·33	17·70
Fine Silt (*a*)	10·68	7·35	11·78	1·00	4·10	4·20	6·39	5·96	11·91	12·62	9·72	7·50	10·63
Fine Silt (*b*)	6·32	1·07	6·39	6·04	6·59	6·30	4·54	13·37	7·47	9·90	6·15	4·08	8·90
Clay	2·74	2·03	6·23	17·81	0·47	2·98	5·33	7·04	10·05	5·88	3·12	1·76	9·49
Moisture	3·27	5·43	6·02	7·69	1·96	2·33	4·40	3·90	2·11	6·62	3·02	2·94	3·84
Loss on ignition	11·81	16·73	20·30	22·12	6·35	10·97	19·19	8·87	13·21	21·36	8·65	7·08	9·45
Loss on solution	3·09	8·25	10·92	14·05	2·68	16·13	30·64	9·30	15·26	8·37	7·23	7·22	1·22

	14	15	16	17	18	19	20	21	22	23	24	25
Fine Gravel	1·08	0·67	0·23	1·70	0·07	4·28	0·70	1·00	—	1·7	1·2	0·5
Coarse Sand	28·71	46·05	11·07	45·84	49·50	50·20	2·40	25·98	3·87	5·7	5·2	15·0
Fine Sand	34·87	30·32	15·48	23·10	35·12	25·70	10·03	48·59	21·17	26·5	32·1	48·9
Silt	8·23	6·86	11·68	3·33	2·47	3·36	19·24	2·58	15·56	20·5	33·3	15·2
Fine Silt (*a*)	5·47	3·57	7·16	3·64	2·98	2·59	13·82	5·16	12·53	9·6	7·4	5·4
Fine Silt (*b*)	3·45	2·67	8·70	1·90	2·73	7·54	12·96	2·70	8·19			
Clay	1·64	1·21	28·25	4·90	1·05	1·68	10·50	0·58	15·27	20·0	11·9	9·3
Moisture	2·14	1·19	3·08	4·40	0·94	0·71	3·04	1·84	4·11	—	—	—
Loss on ignition	6·63	4·69	8·85	13·46	3·28	3·99	26·01	6·99	13·55	—	—	—
Loss on solution	6·19	3·21	3·64	1·68	0·62	0·63	0·91	4·18	4·64	—	—	—

NOTES ON THE SOILS IN TABLE 13

No. 1. Poor grassland derived from coarse millstone grit. Generally under grass at higher altitudes; when cultivated grows principally oats and swedes. Generally requires liming.

No. 2. Grassland soil derived from coal measures sandstone.

No. 3. Grassland soil derived from coal measures at the junction of the sandstone and shale. Intermediate between 2 and 4.

No. 4. Grassland soil derived from coal measures shale.

No. 5. A poor soil derived from oolitic sandstone. Elevation is high and it usually gives rise to moorland or poor pastures growing heather and gorse.

Nos. 6, 7 and 8. Typical "sheep and barley soils" derived from oolitic limestone. The surface soil is frequently shallow and crops, particularly swedes, are apt to suffer from drought.

No. 9. A good natural Humber warp which presents difficulties of cultivation but is otherwise very fertile. Wheat, beans, mustard (for seed), clover and mangolds are the principal crops.

No. 10. A peaty alluvial soil commonly known as "Carr." When limed it grows wheat and mustard (for seed) very successfully.

Nos. 11 and 12. Typical Wold soils formed on a 4- or 5-course rotation. Although derived from chalk, applications of lime are frequently necessary to prevent "Finger and Toe." Barley, wheat and clover are among their most successful crops.

No. 13. A deeper chalk soil and more reliable than Nos. 11 and 12. This soil has been known to carry four successive corn crops.

No. 14. Soil from the valleys or "slacks" between chalk hills, formed by the washing down of material from the hills. It is a deep soil and requires little manuring.

No. 15. Derived from glacial sand in the North Riding of Yorkshire. Barley is one of the best crops if the soil is limed.

No. 16. Derived from a post-glacial alluvial area which is very difficult to drain. When dry, potatoes, corn crops and sometimes mangolds do well. Successful cropping is very dependent upon a dry season.

No. 17. Derived from post-glacial sand, is well situated and grows good crops of barley, roots, seeds and carrots. It requires liberal manuring, but responds well to it.

Nos. 18 and 19. Typical of the "oat, rye and potato" land in the Vale of York.

No. 20. Alluvial soil, difficult to cultivate, but yielding excellent grassland.

No. 21. A gravelly, riverside soil, generally under grass.

No. 22. A heavier type of riverside alluvial soil; generally gives rise to poor grassland.

Nos. 23, 24 and 25 are respectively typical wheat, typical barley, and typical potato soils quoted by Hall and Russell in their survey of Sussex, Surrey and Kent.

carbonate, and generally in the absence of much oxygen, and which are usually quite acid, and (*b*) *fen* soils in which the organic matter has accumulated in the presence of calcium carbonate.

(2) *Calcareous soils*, formed from chalk or limestone.

(3) *Mineral soils.*

Calcareous soils may, in the course of their history, pass into the third group, for carbonate is continually being removed from them and in some areas is entirely absent from the surface soil. In these cases, the soils, although formed from a carbonate rock, are now composed only of the other material—the "impurity"—in the carbonate. The mineral soils cover by far the greatest area and as described in Chapter V, the division of these into sands, loams and clays has been developed and given more precision by making mechanical analyses. The mechanical analysis of a soil has probably figured more than any other factor in the efforts which have been made to classify soils. Whitney in America organized an extensive survey of soils on the basis of their mechanical analyses, and in this country mechanical analysis has been used in the surveys of the South-eastern counties by Hall and Russell, of Shropshire and North Wales by Robinson, and elsewhere. A good deal has been accomplished in correlating the mechanical analyses with the cropping of soils. In Table 13 a number of mechanical analyses are given, and the notes on the soils are given on the opposite page. The differences between soils too heavy for arable cultivation, typical wheat and bean soils, barley soils, potato soils, etc., should be noted.

There are, however, limitations to this kind of work. It is not possible by merely looking at the mechanical analysis of the soil, to say with absolute certainty that it is suitable or unsuitable for particular

crops. Along with the mechanical analysis the amount of organic matter, particularly the humified organic matter, must be taken into account (see page 35) and the lime status of the soil must also be consulted (see page 61). The mechanical analysis indicates the percentage of particles of various grades, but in so far as the arrangement of these particles, in addition to their size, determines soil texture and influences soil fertility, these other factors, organic matter and lime, which have marked effects upon the state of aggregation of the particles, are important. Soils may have the same mechanical analysis and yet differ very much in their fertility on account of differences in their organic matter and lime content. The relationship of the soil to water supply is also important in determining the most suitable cropping and cultivation methods for the soil. A soil with high content of sand may be quite useful under a high rainfall or with a high-water table ; a soil which, judged by its mechanical analysis, is somewhat heavier may, under low rainfall conditions, be nothing but a barren sand. The student will find interesting illustrations of the effects of these various factors in the work of Hall and Russell arising out of their survey of Sussex, Surrey and Kent.

A Practical Classification. It is quite clear that a soil map which merely sets forth the variation in one particular property of the soil (e.g. its mechanical analysis) will be of limited value to the agriculturist. The attempt to combine on one map all the information about the soil which is likely to be of practical value is being made, and specimen maps are being prepared in various parts of the country in which it is hoped to show by appropriate symbols such features as—

(1) Contour (flat, undulating, a slight slope, steep slope, broken and irregular).

(2) Water conditions (seasonal drought, seasonal wetness, subject to flooding, permanent wetness, springs, irrigated).

(3) State of stoniness (no stones, slightly stony, very stony, bouldery, rocky).

(4) Texture of surface layer (grit, light and heavier sand, light and heavier loam, silt, clay, peat, chalk).

(5) Colour when dry.

(6) Colour when wet.

The success of making a map on these lines depends among other things upon the facility and accuracy with which the terms can be standardized, so that such terms as "steep slope," "very stony," etc., will have the same meaning to all workers in all places. It is obvious, of course, that the map produced in this kind of way will not, strictly speaking, be a soil map, it will be a super-imposition of a "contour" map, a "stoniness" map, a "water-conditions" map, a "surface texture" map, and a "colour" map.

The Scientific Classification of Soils

The soil is a consequence of certain processes operating on certain material. In so far as the material from which the soil is formed varies, so it might be thought the soil will vary. Hence the attempts to which reference has already been made, to make a geological classification of soils.

The importance of considering the various processes which operate upon the material as a basis of soil classification was initiated by Sibirtzev in Russia and has since been developed by Glinka and others. Sibirtzev argued that when the soil formation processes have gone on to the utmost, the kind of rock from which the particles were formed would have little, if any, influence on the product, but that a

mature fully developed soil would be dependent upon the processes and conditions involved in its making. In so far as the ultimate fate of the strong bases, sesquioxides and silica are independent and determined by the conditions prevailing, it is clear that as time goes on the product of weathering becomes more and more independent of the special characteristics and crystalline form of the original minerals. In the majority of the soils of Russia climatic conditions have had full play, and Sibirtzev showed that the soils can be grouped according to the climatic conditions under which they were formed.

The development of this work by Glinka has attracted universal attention and is the inspiration of the important soil survey work which is being carried on in the United States. Glinka divides all soils in the first instance into two groups :—

(1) *Immature* or *Endodynamomorphic* soils, in which the processes of formation have not had full play, and in which, therefore, the influence of parent rocks is still apparent.

(2) *Mature* or *Ektodynamomorphic* soils, in which the processes of formation have had full play and the influence of the parent material is at a minimum.

The mature soils are divided into big groups in the way indicated in Chapter IV. These groups may be elaborately subdivided and their subdivision is at present a topical subject of investigation, particularly in Europe.

This kind of classification has been developed by the Russian pedologists from a purely scientific study of the soil which leaves any service it may render to the industry of agriculture to ensue incidentally. Nevertheless the fundamental study must always affect our knowledge and understanding of the more

superficial affairs with which it is connected, and the incorporation of the Russian conceptions into soil work in other countries and by those who are admittedly working in the interests of agriculture, is in no way surprising.

The Soil Profile. From what has been said in Chapter IV about the soil formation processes it will be clear that in general there will be certain layers or " horizons " from which certain of the soil constituents have been leached. The leached materials may be carried away in the drainage water and no longer affect the soil, or they may be deposited in some lower horizons. For instance, in a simple podsol there is an horizon from which the sesquioxides have been largely removed, and a lower horizon in which they and a varying amount of the organic matter have been deposited ; in arid and semi-arid conditions horizons are formed in which various salts (e.g. carbonates and sulphates of calcium and magnesium) are deposited. Following the suggestions of Glinka, the horizons from which materials are leached are called the *eluvial* horizons, and for brevity are labelled " A " horizons. Horizons in which material accumulates are called *illuvial* horizons and are labelled " B " horizons. The soil profile may contain several A horizons and several B horizons. These are labelled A_1,* A_2, etc., B_1, B_2, etc., from the top downwards. Even in a simple podsol there are usually two A horizons, the upper one containing much organic matter and the lower one containing little organic matter and having a white bleached appearance in consequence of the removal of the iron. One particular horizon may sometimes be a B horizon in respect of one constituent and

* The surface layer in grassland and woodland is generally designated A_0.

KEY TO FIGS. 12, 13 AND 14.

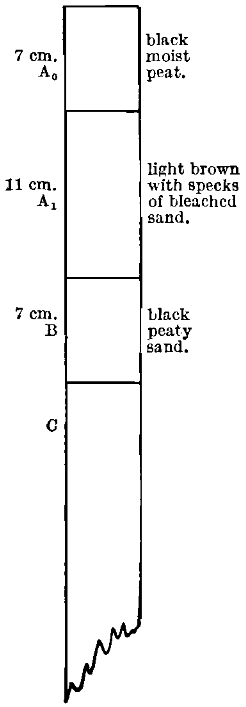


FIG. 12.
Denton Moor (Yorks).

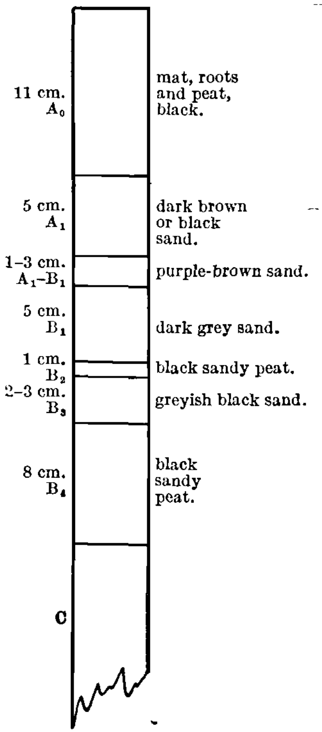


FIG. 13.
Denton Moor (Yorks

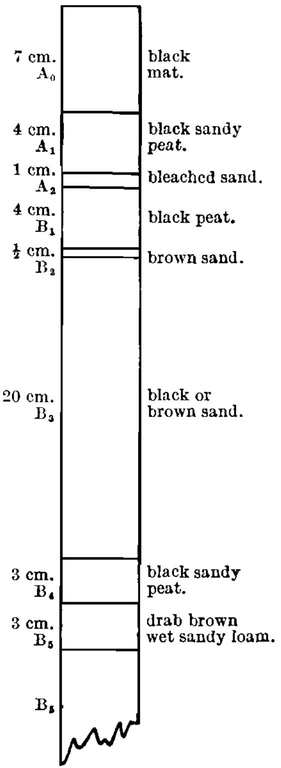


FIG. 14.
Middleton Moor (Yorks).

KEY TO FIGS. 15 AND 16.

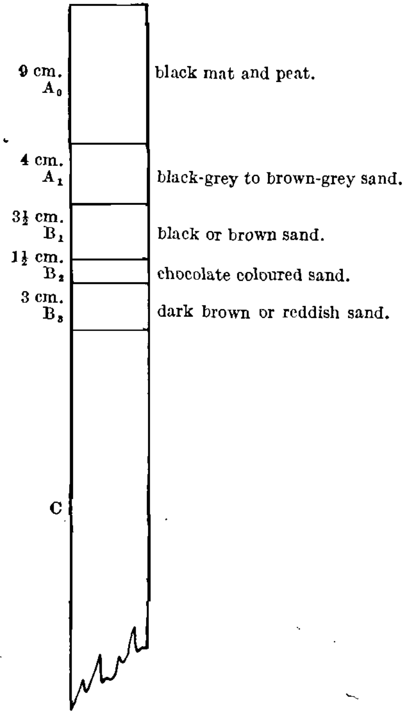


Fig. 15.
Middleton Moor (Yorks).

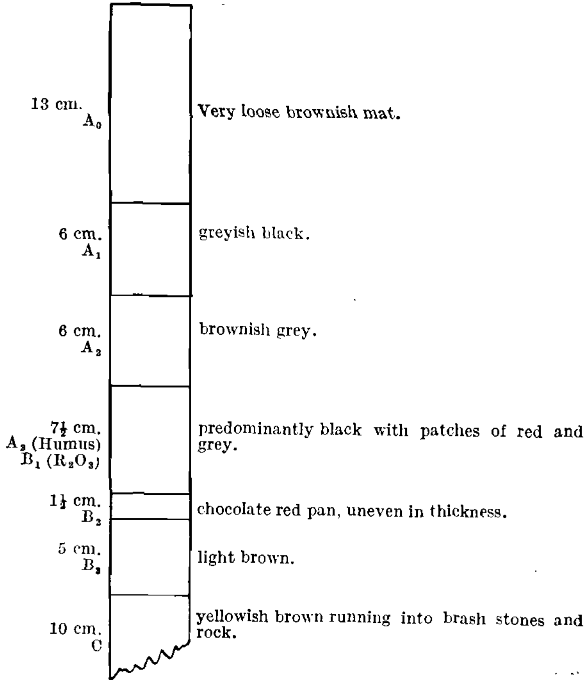


FIG. 16.
Harlow Quarry (Harrogate).

TABLE 14

Harlow Quarry Profile (Fig. 16).

(J. S. Willcox)

	Silica.			Fe_2O_3.	Al_2O_3.	CaO.	Moisture.	Loss on Ignition.
	Alk. Sol.	Acid Sol.	Insol.					
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Top Layer, 13 cm.: Very loose brownish mat	1·24	0·09	35·95	0·87	0·67	0·165	6·55	54·52
2nd Layer, 6 cm.: Greyish black	0·63	0·12	88·28	0·23	0·028	0·050	2·79	7·25
3rd Layer, 6 cm.: Brownish grey	0·99	0·13	93·77	0·12	0·67	0·030	1·03	3·56
4th Layer, 7½ cm.: Predominantly black with patches of red and grey	2·24	0·16	78·31	2·59	0·20	0·025	2·33	13·00
5th Layer, 1½ cm.: Chocolate red pan, uneven in thickness	1·65	0·07	63·31	8·81	2·56	0·015	8·24	14·34
6th Layer, 5 cm.: Light brown	3·05	0·10	70·07	6·99	2·59	0·020	3·72	13·70
7th Layer, 10 cm.: Yellowish brown running into brash stones and rock	2·79	0·08	85·21	3·06	2·33	0·040	2·58	3·30

an A horizon in respect of another. For instance, organic matter is sometimes leached downwards and deposited in a B horizon. Its presence there may cause the removal of sesquioxides from that horizon (i.e. a process of podsolization beneath the surface), and the horizon will therefore be an A horizon in respect of the sesquioxides. References to Figs. 12–16 on page 142 and to Table 14 will show that the profile may sometimes be very complex.

One of the most important developments of the Russian studies of soil genetics has been the examination of the profile. The classification of soils on the basis of their physical properties which was organized by Whitney in America with notable results has now given place to the mapping of soils on the basis of their profiles under the direction of Marbut. Profiles of uncultivated land are examined and the number and thickness of the separate horizons are noted. The texture profile is then recorded by examining the texture of each horizon. The colour profile is examined and certain chemical determinations are made on each horizon. Areas in which the profiles are essentially alike are grouped together and the characteristic profile is given a definite name (e.g. "Brooke Silt Loam," "Ruston Fine Sandy Loam," "Fargo Clay," etc.) and description. The description of one particular type taken at random from the U.S. Survey will indicate the style of description given :—

"Cecil Clay Loam.

"The surface soil or horizon A_1 of the Cecil Clay Loam in the virgin or wooded areas consists of a dark brown loam 1 to 3 inches in depth. This is underlain by horizon A_2 which is a reddish brown clay loam to a depth of about 4 to 5 inches. The subsoil or horizon B_1 is a red stiff but brittle clay which extends to a depth of 4 or 5 feet and even deeper in places.

This grades into a light red friable crumbly clay carrying a large amount of mica, and this is also usually 1 to 2 feet in thickness. This may be termed horizon B_2. This is underlain by horizon C, which is a yellowish red, friable, disintegrated and partially decomposed rock. In the cultivated fields the surface soil is red or reddish brown clay loam to a depth of 5 to 7 inches, the colour and structure here being due to the amount and condition of organic matter. This soil is locally known as 'red clay land' or the Piedmont Plateau."

Surveying on the basis of the soil profile has two important characteristics.

(1) *It considers the soil as a whole.* No other process of classification does this. It is frequently said, referring to a particular area, that the soil has a certain mechanical composition, which statement implies that the mechanical analysis of the soil is uniform throughout its depth. Except in the case of certain new warp soils, this is probably never true. The study of the profile differentiates between the texture factors of different horizons. The same consideration applies to any other characteristic which may be studied separately in each horizon.

(2) *It takes cognizance of the soil formation processes.* The processes going on in a soil effect removals, leachings and depositions and the soil profile reflects these processes. The importance of this cannot be exaggerated, for it is a philosophical necessity that one cannot claim a scientific knowledge of soil without a knowledge and understanding of what has gone on in its formation, and what is still going on within it. Hitherto there has been too great a tendency to consider the soil statically, and to try and visualize its constitution as a fixed thing.

Immature, Cultivated and Sedimentary-rock Soils. In soils which are immature and in which the soil processes have not had full play some of the char-

acteristics of the parent material still obtain. The characterization of such soils involves a combination of the two considerations, namely, the parent material and the processes acting upon it.

In cultivated soils the upper part of the natural profile is disturbed by cultivation processes which prevent the formation of horizons within the depth of their influence, and tend to make the soils uniform. This disturbance of the upper horizon or horizons may have considerable effect upon the lower horizons.

Soils which are formed from sedimentary rocks such as the clays and sands of this country, will not, under uniform weathering conditions ultimately become alike in all respects. The rocks from which they are formed are the results of a sorting-out process in which the larger particles have been approximately separated from the smaller ones.

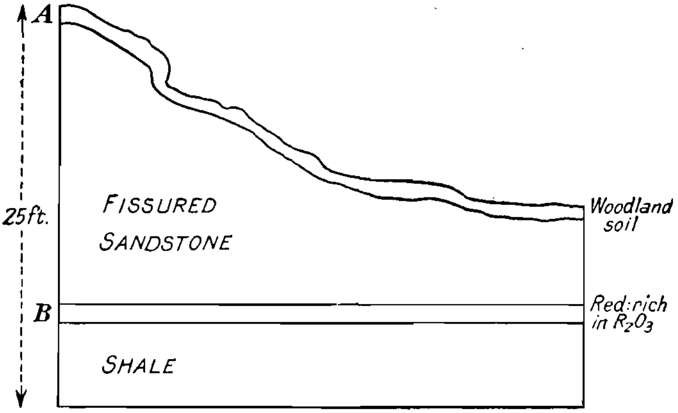


FIG. 17.—Near Leeds. Two pedological horizons separated by a geological horizon, the sesquioxide having passed through the fissures in the sandstone.

It may be thought that the considerations underlying the genetic classification of soils are of less impor-

tance in all these cases and therefore of less importance in this country. There is, however, a sense in which those considerations are of *greater* importance in the study of such soils. Crudely speaking, the soil processes have gone on to the utmost in the mature soils, and the processes are easily discovered by the examination of the soil. In the immature and cultivated soils the processes are going on and the soil itself does not so clearly indicate what these processes are. But the knowledge of these processes is equally important; indeed it is fundamentally important. The study of the soil formation processes is much *more difficult* in a country of immature and cultivated soils than in a country of mature soils, but it cannot possibly be less important.

Profile studies in Great Britain have only recently been undertaken. Work on these lines is being carried out in Scotland by Newlands and by Ogg, in North Wales by Robinson, and in Yorkshire by Trefor Jones and others.

CHAPTER XIV

THE ARTIFICIAL TREATMENT OF SOIL

The preceding chapters have been mainly concerned with the constitution of soils and natural soil phenomena. It is now desirable briefly to review the principal operations employed to maintain and enhance the crop-producing power of soils, considering these operations in relation to the previously described phenomena, and to consider the methods of determining the effect on the soil and the crop of any particular treatment.

The Chief Effects of Processes of Soil Treatment

Drainage. Excessive water in a soil automatically involves inadequate aëration, lowering of temperature and limited root range. All these conditions are directly inimical to seed germination and crop growth and the insufficiency of air and the reduced temperature militate against the formation of nitrates. The lowering of the water table by the suitable laying of drains tends to remove these undesirable conditions and, although water is removed from the soil, the enhanced root range puts the plant in a position to draw on more water than is available in the undrained condition.

In some of King's famous experiments it was found that the difference of surface temperature between drained and undrained land was sometimes as great as 12° F.

Autumn Ploughing. Ploughing is the only common cultivation process in which the upper layer of soil is turned over. The effect of this is to bury surface organic matter and incorporate its decomposition products and humus with the soil. The zigzag surface produced by ploughing facilitates the percolation of winter rainwater into the soil and reduces the losses due to running off and evaporation, which may easily amount to 50 per cent. of the rainfall in the climate of Britain. Moreover, the exposure of the furrows to alternate wetting and drying out, and to alternate freezing and thawing, increases the formation of soil crumbs and aids the "breaking down" of the clods of a heavy soil with a consequent improvement of texture and condition.

Spring Ploughing. Soil is sometimes ploughed in the spring to enable the surface layer to dry out slowly and crumble in a condition suitable for making a good seed bed. Also the mulching effect of the furrows is significant at a time when drier weather and greater loss of water by evaporation is likely to set in, and the increased air supply facilitates nitrate formation.

Hoeing and Mulching. Whether it be by using an artificial mulch of straw, etc., or by hoeing the surface of the soil, any loose material which involves a discontinuity of the water film between the lower layers and the surface exposed in dry weather to the atmosphere will reduce the loss of water from the lower layers. Spring ploughing incidentally accomplishes this to some extent: hoeing is more effective. In some of King's work it was shown that mulching 1 inch deep may reduce the amount of water lost by evaporation from the surface by 30–50 per cent. Deeper mulches are still more effective.

Equally important is the aëration of the surface soil and the enhancement of nitrification, and crops growing in spring and summer in properly mulched land are much less dependent on nitrogenous fertilizers than such a crop as winter wheat.

Rolling. When soil is rolled and the particles and their aggregates are pushed together, the conditions become favourable for a continuous water film from the surface down to the water table. In dry weather the water evaporating from the surface will continually be replaced by water moving up from below. This involves a considerable loss. Nevertheless it is frequently necessary to incur the loss for the sake of bringing moisture to germinating seeds and young plants in the surface soil. When the plant roots have penetrated to a greater depth the surface should be hoed and the film broken.

Bare Fallowing. The practice of leaving land uncropped for a season is very long established. To a large extent the facilities for cleaning the land justify the practice, but over and above that there is an evident tendency for a bare fallow to bring about some improvement in the succeeding crop. The reasons for this improvement may not yet be fully understood, but it is known that the enhanced production of nitrate in uncropped land is one important factor, and the effect of the fallow is considerably reduced in a rainy season when the nitrates are largely leached from the soil.

Addition of Organic Matter. Organic matter is added to soils in a variety of ways: green manuring (the ploughing in of a crop), application of farmyard manure and so forth. The consequent addition of humus to the soil has important effects on the soil texture, and fertility is further affected by the stimulus given to the

important micro-organic population of the soil. When leguminous crops such as tares and vetches are ploughed in, there is the further advantage of enriching the soil in nitrogen. Green manuring tends to reduce the incidence of common scab in potatoes.

Liming. The influence of lime on the soil is very diverse. On heavy clay soils its action in aggregating the particles and improving the texture is important. Highly unsaturated soils on which sour conditions prevail are brought to a higher degree of saturation, frequently with extraordinary improvements in fertility. The flocculation of the clay particles and the increased lime status improve the conditions of micro-organic life and stimulate bacterial activity. This effect is perhaps most apparent on certain grassland in which bacterial life has been so reduced that a "mat" of dead grass has accumulated. The proper incorporation of lime in such a surface sometimes brings about the complete destruction of the mat in the course of a very few years! Large applications of quicklime sometimes effect the partial sterilization of the soil.

Addition of Fertilizers. It has already been mentioned that while the elements required by the growing plant are fairly numerous, fertilizers containing compounds of nitrogen, phosphorus and potassium are those most commonly used in practice, and those from which increased yield is most likely to arise. The use of these fertilizers is very largely based on empirical experience, and one of the pressing industrial problems which besets soil chemists is the determination of what fertilizers are likely to be most useful and in what quantities they should be applied to any given soil area. The remainder of this chapter is devoted to a brief account of the methods adopted in this matter.

The Determination of the Effects of Treatment

Most of the processes of soil treatment enumerated above are the outcome of experience. For example, the useful results following applications of farmyard manure and of lime were known as far back as the date of any written record. Agriculture has always been an art; only in recent times has the scientist given attention to the matter and carried out work designed to consider critically the justification for time-honoured processes, to discover their rational explanation, and conceivably to improve them and add to their number.

Single Plot Experiments. When attempts were first made to get exact information about the results of soil treatment the obvious thing was done. Two areas were marked out; one received the treatment in question, and the other did not, and the quality and yield of the crops from the two areas were compared. Many of these experiments have confirmed former tradition and many of them have initiated new practices. There are some of these experiments whose results are evident beyond dispute: there are others in which the results have been doubtful, varying from place to place and from year to year. When for example the yield on the treated plot is consistently something of the order of 50 per cent. greater than that from the untreated plot and still more when the difference is visible to the eye and the line of demarcation between the plots is seen in the crop, there is no doubt that the treatment has effected an increase. On the other hand, when the differences are small, say 5–10 per cent. and no visible demarcation between the plots is seen in the crop, no reliable conclusions can be

drawn. Such small differences may very well arise even if the plots are not treated differently, for the lack of uniformity in the crop-producing power of practically all soil areas is considerable and much greater than is apparent to the eye. It appears to be doubtful whether even experienced agriculturists can detect a difference of 15 per cent. or even 20 per cent. between two adjacent corn crops. Choosing uniform land for plot experiments is therefore not as easy as might appear. Possibly the uniformity of ripening of a crop is the best criterion.

If any particular soil treatment has a positive effect

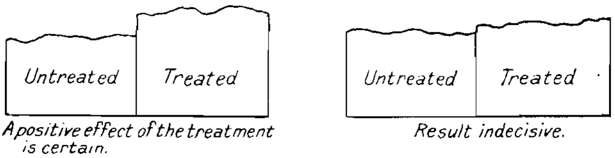


FIG. 18.—Diagrammatic Illustration of the Two Extremes of Results of Single Plot Trials.

on a crop there will in the ideal case be a sudden increase in quantity or some point of quality as one passes from the untreated to the treated plot. The determination of that sudden change is the crucial problem in deciding qualitatively whether the treatment has or has not an effect. The student should clearly distinguish between the two extreme cases illustrated diagrammatically in Fig. 18, in one of which an abrupt change is obvious and in the other of which that change is obscured by its own smallness and soil variation. The case in which abrupt change is obvious is straightforward qualitatively and is not usually difficult to deal with quantitatively. The case in which the abrupt change is small and obscure can only be dealt with—even qualitatively—as a

probability determined by replication in various ways.

Testing the Uniformity of Land. Attempts have been made to overcome this difficulty by treating the two plots similarly for a year or two before initiating the experiment. Thus on the Manor Farm at Garforth in Yorkshire there is a series of meadow hay plots, differently manured, and since 1912 one-half of each plot has been limed and the other not. For three years before the liming the yields of hay from the two halves of each plot were recorded and the average difference between them is allowed for in estimating the increase due to liming. Some of the initial differences between the two halves were as high as 11 or 12 cwt. per acre.

This preliminary testing of the ground is very useful, but unless it can be carried on for a number of years it may not help as much as might be thought, for considerable differences in the differences are sometimes found from year to year.

Replication of Plots. The replication of the plots in various places and the continuance of them for several years may admit of conclusions being drawn where that would be impossible for any one of the experiments in any one year, and it is usual in laying down experiments designed to test any treatment which is not likely to give an overwhelming difference to replicate the plots. This replication of the plots, however, introduces further difficulties, for the treatment which is being investigated may have a definite and demonstrable effect in one place, and may have no such effect in another. For example, in the many trials of various phosphates and slags which have been carried out in this country there is abundant evidence that the phosphate has affected the crop in a marked manner at

some centres, and not at others. The duplication of the experiment *in another place* does not therefore necessarily help towards a decision as to the effect of the treatment at the original centre. With sufficient data from properly replicated experiments, the statistician may be able to state the probability of a particular treatment having an effect on some untreated land. That, however, is a different and a less useful thing than being able to differentiate between those

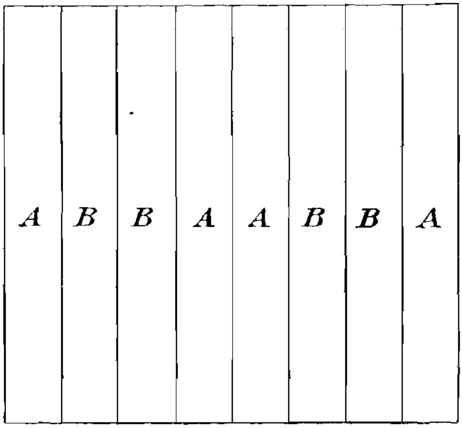


FIG. 19.—The "Half Drill" Arrangement of Plots.

areas in which the treatment is likely to yield positive results, and those areas in which it is not. Such information, and at best only limited, can only be expected from a study of the results of the replicated experiments taken in conjunction with a study of the type of soil involved.

The Half-Drill Method. A method of replicating plots on one field and which is mainly of use in comparing two varieties of corn is illustrated in Fig. 19. In variety trials the seed of one variety is put in one

half of the drill box and the seed of the other in the other half. While this method involves some practical harvesting difficulties it has great advantages over a mere replication of larger plots. It is possible, for instance, to form some idea of the soil variations by *noting any regular increases and decreases along the* series of plots of the same variety all similarly treated.

The Use of an Interpolated Standard. A method of arranging plots is illustrated in Fig. 20 which is

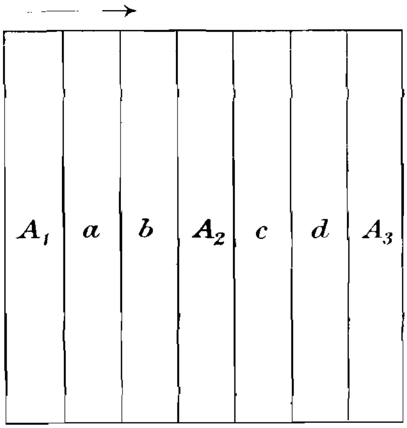


FIG. 20.—The "Interpolated Standard" Method of Plot Experiment

useful when there is evidence of a regular variation of the soil at right angles to the plots. The plots, A_1, A_2, etc., are replicates of the "control" plot—i.e. the untreated plot or the standard variety. The plots, *a*, *b*, *c*, etc., represent different treatments or varieties. If there is a regular soil variation in the direction of the arrow, the yield of a control plot where "*a*" is would be $A_1 + \frac{A_2 - A_1}{3}$ and the ratio of the yield of "*a*" with that of a control plot on the same ground is

$$\frac{a}{A_1 + \frac{A_2 - A_1}{3}} \text{ or } \frac{3a}{2A_1 + A_2}.$$

This method has been used for variety trials in Australia.

The Balanced Plot Method. Fig. 21 illustrates

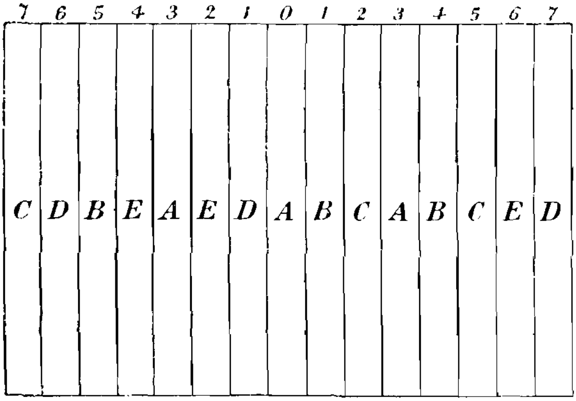


FIG. 21.—The Balanced Row Arrangement of Plots.

an arrangement of plots in triplicate. The feature of the arrangement is that the distance in one direction of one of three similar plots from the middle is equal to the sum of the distances of the other two in the other direction.

The Chessboard Method or "Latin Square." A device introduced many years ago for attempting to deal with the difficulties of soil variation is illustrated in Fig. 22. In the illustration four different treatments or varieties are catered for, but the square can be adapted to accommodate less or more. The four plots are arranged in quadruplicate in such a way that each appears once in each vertical series and in

each horizontal series. The sum of the yields from the four different treatments may be obtained in eight different ways, by four vertical and by four horizontal additions. If the land were perfectly uniform and the experiment entirely devoid of errors, these eight totals would be identical. In practice they will vary and the application of simple mathematical considerations to the extent and manner of the variance admits of some

A	*B*	*C*	*D*
D	*A*	*B*	*C*
C	*D*	*A*	*B*
B	*C*	*D*	*A*

Fig. 22.—The Chessboard or "Latin Square" Arrangement of Plots.

conclusions being drawn about the variation in the land and a correction being made to the observed yields in each of the sixteen squares. This method fell into disfavour among agriculturists on account of harvesting difficulties, but has been recently resuscitated at Rothamsted.

The squares can be arranged in a very large number of ways to fulfil the requirement that no one treatment appears more than once either in the vertical or horizontal series. The Rothamsted plan is to put all the possible arrangements on cards in a hat and by

drawing one out thus to fix the arrangement used by chance.

The proper control of field experiments in which relatively small differences of yield obtain is a much more intricate matter than was until recently supposed, and in designing an experiment of any importance it is advisable for the agriculturist to consult the statistician.

Pot Experiments. The difficulties consequent upon the lack of uniformity of soil conditions may be very largely overcome by carrying out experiments with small quantities of soil in suitable pots after previously thoroughly mixing all the soil involved in the experiment. Pot experiments, however, are not so simple as is frequently supposed. While the soil used may be made uniform by artificial mixing, the difficulty of filling several pots so that the state of compactness will be the same in all is very great. It is not usual to obtain any satisfactory conclusions from pot experiments in which small differences are involved unless the experiment is carried out at least in quadruplicate. Moreover, the conditions under which the soil is held are artificial and the important connection with other soil round it and subsoil and rock below it is broken.

Useful results can, however, be obtained by carefully conducted pot experiments, but they frequently involve more trouble than many field experiments, and it is not always possible to transfer the results obtained to practical circumstances.

The Laboratory Examination of Soils. Sufficient has been said in earlier chapters to show that the interpretation of the results of soil analysis is for the most part very obscure. Nevertheless it is possible to obtain some information in the laboratory as to the possible response of a soil to a particular treatment,

Mechanical analysis considered in conjunction with the lime status, humus content and water conditions is of value in considering treatment to meet difficulties of texture and tilth. It sometimes enables the agriculturist to say whether the difficulties in question are inherent in the soil itself or arise from external influences such as situation and climate. The mechanical composition is an important factor in deciding whether heavy land shall be laid down to grass or whether liming and careful management may admit of its being retained under arable cultivation.

The chemical analysis of soils is of more value in some problems than in others. The usefulness of the lime requirement methods in deciding whether the lime status of the soil is adequate for the proposed crops has been discussed (p. 100). The value of determining the so-called "available" phosphate and potash by extraction with dilute acid is perhaps less, but nevertheless appreciable.

Laboratory methods of examining soils are still to some extent in the experimental stage, and the application of their results to agricultural problems is still more so. The general tendency at the present day is to endeavour to accumulate as much data as possible about the correlation of the laboratory results with experience in the field, and by surveying and mapping the soils to seek some knowledge which will enable one to connect any particular soil that comes under consideration with a similar and similarly situated soil about which the relation of response in the field to laboratory results is known.

CHAPTER XV

THE LITERATURE OF SOIL SCIENCE AND ITS USE

The general student of Agriculture, who necessarily pursues a course of study in the science of the soil, should acquire three things from that course. First, a general knowledge and understanding of soil science as it is viewed at the time of his course of study; second, a competence to acquire more detailed knowledge of any special part of the subject that may for any reason become his special—even though temporary—concern; third, a competence to follow intelligently the future development of the subject. He must therefore know something of the literature. Naturally the specialist will have a more detailed knowledge of the literature of his speciality, but the agriculturist should "know his way about" this literature. This chapter is an effort to direct him, although perhaps not to guide him.

The Literature

Books. By general consent two present-day books in this country are pre-eminent.

"*The Soil,*" *by Sir A. Daniel Hall.* This book marked, by its first edition in 1903, the consummation of an important period in the development of soil research. Its latest and third edition, published in 1920, incorporates subsequent advances. It is written without the assumption of much knowledge of chem-

istry and physics and caters for the educated farmer as well as the college student. It contains abundant practical illustrations and examples of the principles described.

"*Soil Conditions and Plant Growth*" (*fifth edition,* 1927), *by Sir E. John Russell.* This may fairly be described as a "Reference Library" of the subject for the general agricultural student and a comprehensive necessity for the specialist. It gives a full account, with abundant references, of the science of soil conditions. The historical introduction is a valuable feature.

"*Physics of Agriculture,*" *by F. H. King,* of the University of Wisconsin, includes some of the most important work on soil physics. Problems of water supply, air and temperature are dealt with very fully.

Journals, Reports, etc.

Internationale Mitteilungen für Bodenkunde. Proceedings of the International Society of Soil Science. The "Internationale Mitteilungen" was initiated mainly by the European soil chemists in 1911. In 1924 after the publication of its 14th volume, it was transformed into the "Proceedings of the International Society of Soil Science" which society was formally founded in that year. These Proceedings are published quarterly in English, French, German, Italian and Spanish at the International Institute for Agriculture, Rome, and constitute a part of the "International Review of the Science and Practice of Agriculture."

In addition to this quarterly publication, the Proceedings of Conferences of the International Society and its constituent "Commissions" are published separately.

These publications are definitely scientific and are admittedly of chief importance to the specialist.

The Journal of Agricultural Science was launched in 1905 by British agricultural scientists. Its inception was largely an effort to rescue a considerable amount of technical and scientific matter from the comparative oblivion of college bulletins, leaving these bulletins free for service to farmers. It has become indispensable to any soil library.

The Journal is published quarterly. It deals with the whole realm of agricultural science but contains most of the important soil papers published in this country. Some of its matter is technical and more suitable for the specialist, but many important papers should be quite clear to the agriculturist.

Unfortunately the Journal has no official collective index, but most agricultural schools will presumably have one of their own making.

Soil Science was initiated in 1916 by Rutgers College in the United States, with Dr. Jacob G. Lipman as editor-in-chief. It is published monthly and has now (1927) reached its 23rd volume. It contains nearly all the important American soil papers, and is a necessity in any Soil Reference Library.

There is an exhaustive index to each volume, but no collective index as yet.

The Journal of Agricultural Research is an official publication of the United States Department of Agriculture and was initiated in 1913. This journal is largely devoted to biological problems of agriculture, but there are occasional soil papers of importance.

Die Landwirtschaftlichen Versuchs-Stationen is a very old journal of agricultural science. Some classical soil papers are published in the earlier editions, and some important ones in more recent volumes.

Miscellaneous. There are some noteworthy soil papers, although mainly of more interest to the special-

ist, in *The Proceedings of the Royal Society.* The journals of almost any of the general scientific societies —e.g. *The Journal of the Society of Chemical Industry* —occasionally publish soil papers. *The Faraday Society* has twice held a symposium on soil subjects—" Physico-chemical Soil Problems " in 1921, and " Base Exchange Phenomena " in 1925. The papers are published in the Society's Transactions. There is also a considerable amount of soil matter distributed through the many bulletins of agricultural colleges and research stations. Much of this is often very inaccessible, but its amount is rapidly diminishing under the influence of the established journals.

Abstracts, Resumés, etc.

Annual Reports of the London Chemical Society. This yearly report of the progress of chemistry has one section devoted to soil chemistry. This section of the report should be perused by all who wish to follow the advance of the subject.

Experiment Station Record. The United States Department of Agriculture inaugurated under this name an extensive and systematic series of abstracts. The name of the publication hardly does it justice for all papers of agricultural importance, and not merely those from Experiment Stations, are abstracted. Not only the section on " Soils and Fertilizers," but also that on " Agricultural Botany " contains matter of interest to the soil student.

Every agricultural student should make the acquaintance of the Experiment Station Record, which is probably the best set of agricultural abstracts obtainable. Its chief drawback is that its abstracts are not usually available in this country until some considerable time after the publication of the papers that are abstracted.

The Record is now (1927) in its 40th volume and each volume is indexed.

Chemical Abstracts is a publication of the American Chemical Society which was commenced in 1907 and is published twice a month. Section 15 is devoted to abstracts of papers relating to soils and fertilizers.

British Chemical Abstracts. B. Applied Chemistry, XV, Agriculture. The London Chemical Society and the Society of Chemical Industry have recently made a collaborative effort to produce something corresponding to the American Chemical Abstracts. The Bureau of British Chemical Abstracts which was thereby established now publishes monthly in association with the Journal of the Chemical Society, "British Chemical Abstracts. A. Pure Chemistry"; and fortnightly in conjunction with the Journal of the Society of Chemical Industry, "British Chemical Abstracts. B. Applied Chemistry." The "B" Series, section XV (Agriculture), contains useful abstracts of many soil papers.

Die Jahresberichte für Agricultur Chemie is a German production of very long standing devoted to Abstracts. It has periodic collective indexes.

Physiological Abstracts and the American *Botanical Abstracts* both publish abstracts of soil papers calculated to interest physiologists and botanists.

There is naturally much repetition of labour in abstracting, many papers being abstracted in all the abstracting publications. This, however, is not wholly unfortunate for the abstracts vary considerably and it is often possible to get a much better conception of the paper from several abstracts together than from any one of them alone.

Agricultural Periodicals. There are a number of agricultural journals which frequently contain resumés

of soil investigations and abstracts of recent papers. Some of the chief of these are *The Journal of the Ministry of Agriculture and Fisheries*, a Government publication founded in 1894 and published at first quarterly but now monthly; *The Scottish Journal of Agriculture*, published quarterly since 1918 by the Stationery Office, Edinburgh; *The Proceedings of the Royal Agricultural Society* (yearly); and the *Transactions of the Highland and Agricultural Society of Scotland* (yearly).

There are many books, journals and abstracts pertaining to the subject other than those mentioned above. The selection of those named is not intended necessarily to imply a meritorious distinction between them and the others, and it is hoped that the selection will not be deemed invidious. The books and journals named are those commonly used in the author's experience, and the student who is familiar with them will inevitably find reference—particularly in the abstracts—to others.

The Use of the Literature

It has been indicated at the beginning of this chapter that there are two general reasons for the serious student of scientific agriculture necessarily having a general familiarity with the literature of the science of the soil. One is that he may have occasion to consider in some detail the work done on a particular problem, the other is that he must be able to keep in general touch with the whole development of the subject. No "rules" can be attempted for the achievement of these two ends, but the following general remarks may be useful.

Surveying the Literature of a Specific Problem. The agriculturist who needs to ascertain whether any investigations have been carried out on a particular

subject, and if so, with what results, will in the first instance naturally turn to such books on the soil as are available and will particularly search the bibliography and references in "Soil Conditions and Plant Growth."

Many institutions concerned with the subject will have a card index that may be useful, but the subject of soil science is so diverse that references in the most complete card index may not be grouped together in the manner required, and in using a card index one has to consider every possible heading under which references to the particular problem might be found.

The indexes of the Experiment Station Record and other abstracts will be consulted, usually starting with the most recent issue and working backwards as far as is thought necessary. Care has to be taken to think of every possible word under which the subject might be indexed, for it is easily possible to miss the reference one wants because the indexer has put it under a word which does not occur to the reader. So far as is possible the original papers abstracted should be seen. It is not *always* necessary to read them in every detail, as many of them have a few pages of summary and conclusions at the end.

When searching for papers dealing with a particular problem, one frequently finds one paper which gives a resumé of work on that problem up to the date of its publication and the student may therefore often make use of the labours of other people.

The particular procedure adopted, however, depends on the problem and the extent to which one wishes to be acquainted with its detail. Experience of using the literature is the most effective way in which one can decide how to proceed in respect of a particular problem, and these remarks are made in the hope

of stimulating the student to acquire some such experience.

Surveying the General Development of Soil Science. For this purpose it is still less possible to indicate a systematic procedure. In the agricultural periodicals such as those named on page 166, there frequently appear resumés of recent developments and at least some of these journals should be perused regularly. The Annual Reports of the Chemical Society will be useful in this connection and the agriculturist who wishes to keep his knowledge of the soil abreast of the times should take what opportunities are possible of looking through the later issues and editions of some of the journals and books with which he became acquainted during the period of systematic study.

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APPENDIX A

COLLOIDS

Solutions on the one hand and suspensions and emulsions on the other are familiar systems, and the difference between them is generally understood and appreciated. In solutions matter in its finest state of division is distributed through a liquid and the particles of solute, which are of molecular dimensions, cannot be seen by any known device. In suspensions and emulsions matter in a relatively coarse state of division is distributed through a liquid ; the particles or droplets can be seen either with the unaided eye or with a microscope : they can always be seen in mass in so far as they give the system a turbid appearance. The difference between these two kinds of systems is, however, only one of degree. In each of them there is a solvent, or *continuous phase*, and in each of them there are distributed particles, or a *disperse phase*. Between them every stage of graduation from the dispersion of invisible molecules to that of visible particles may exist. It is theoretically possible, and indeed practically possible, to arrange a series of aqueous systems with a "true" solution at one end and a manifest suspension at the other but with an imperceptible difference between any one member of the series and the next. There are systems which on casual inspection look like "true" solutions but whose dispersed particles are actually visible when viewed through an ultramicroscope, and whose "solutes" diffuse very slowly and partially through many membranes. These intermediate systems are the *colloidal solutions*. They were first recognized by Thomas Graham by the reluctance of their solute to diffuse through parchment.

Roughly, but conveniently, dispersed substances in aqueous colloidal solutions may be considered in two groups.

1. There are those (e.g. gold, platinum, and other metals) whose dispersed particles have no appreciable solubility or affinity for water and in colloidal solution may be considered to present a "clean" and well-defined surface to the surrounding liquid. These are sometimes called *suspensoids* or *hydrophobic colloids.*

2. There are others (e.g. silicic acid, proteins) whose particles have an affinity for water. Between the particles and the surrounding water there are all stages of transition —the transition from suspension to solution on a small scale. These are often called the *emulsoids* or *hydrophilous colloids.*

The dispersed particles carry an electric charge and migrate accordingly under a potential difference. Particles in water are usually but not always negatively charged. If this charge is neutralized the particles tend to come together and to be *precipitated* or *flocculated* and so deposited from solution. Electro-negative particles are flocculated by cations, notably the hydrogen ion, but tend normally to be stabilized by the hydroxyl ion. Speaking generally, the so-called emulsoids are more stable and less susceptible to the influence of electrolytes than the suspensoids, many of which are influenced by the merest trace of electrolyte. When suspensoids and emulsoids are together in colloidal solution the emulsoid may stabilize or *protect* the suspensoid.

Colloidal solutions are commonly termed *sols.* Many of the dispersed substances when precipitated from their sols appear as gelatinous precipitates or *gels.*

Colloidal particles are relatively very small and there is in consequence a very large total surface belonging to a given weight of material. Reactions, whether physical or chemical, which take place at the surface are therefore very pronounced. Colloidal gels can "adsorb," i.e. concentrate on the surface, many constituents of solutions in very appreciable amounts. When this happens there is a distribution of the solute in question between the solution

and the gel. This distribution usually complies with the equation

$$y = ac^{\frac{1}{n}}$$

where y = amount "adsorbed" by the solid phase.
c = concentration in solution.
a and n are constants.

Until recently it was supposed that compliance with this equation was proof of a *physical* adsorption, but this view has been considerably broadened, particularly with the disappearance of a definable boundary between physical and chemical phenomena.

APPENDIX B

SURFACE TENSION AND CAPILLARITY

In a mass of liquid there is a mutual attraction between the molecules. A molecule below the surface as at *A* in Fig. 23 is equally attracted in all directions, being uniformly surrounded by other molecules. A molecule of the liquid at the surface as at *B* is not completely surrounded by other liquid molecules, and is therefore not attracted in all directions alike. It will receive a resultant attraction

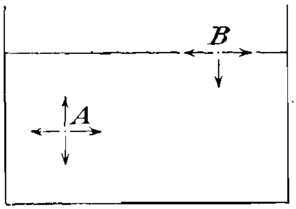

FIG. 23.

tending to pull it into the liquid. This unbalanced pull which the surface molecules receive produces a tension at the surface of all liquids. This *surface tension* is more accurately considered as an *interfacial tension*. It is really a tension in the interface liquid-air. For the present purpose it may be considered as a surface tension, and the student is entitled to regard it as an imaginary elastic membrane covering the surface. Picturing the surface tension as an elastic membrane may, however, lead to one error against which the student must be warned. If a drop or a film of water exposing a certain surface is spread out in some way so as to expose a larger surface, it might be thought that the surface becomes "stretched" and

that, therefore, the tension per unit area becomes greater. A little consideration will show that this is not so. When a film of water is deformed, to expose a larger surface, *that larger surface does not arise by a stretching of the original smaller one*, but by the removal of more molecules from the bulk of the water to the surface. *It is due to an increase* in the material making up the surface. The larger surface is not larger because it is more stretched as the larger surface of stretched elastic is. It is larger because there is actually more of it. *The extent or degree of stretching remains the same* if the temperature does not change. The surface tension of water at 20° C. is 72·7 dynes per cm. The imaginary elastic membrane at the surface must therefore be pictured as one which at any given temperature is in a state of constant and fixed tension. When the membrane is enlarged it is enlarged by the introduction of more material (from the bulk of the liquid) which on coming to the surface assumes the same state of tension; and when the surface is reduced it is reduced by the actual removal of material from the surface to the bulk.

The Pressure at Curved Water Surfaces. If the surface of a liquid is level, as in Fig. 24, *a*, a molecule x in that surface will be subjected to an inward pull or pressure P. If, however, the surface of the liquid is concave, as in Fig. 24, *b*, the inward pull on a molecule x will be less than P. In the level surface the attractions of neighbouring molecules *in the surface film* are all in one plane and their resultant is *nil*. In the concave surface the attractions of neighbouring molecules in the surface film are not in the same plane, and their result is an upward pull p. The net inward pull or pressure on a molecule x will, therefore, be $(P - p)$. The value of p will be greater the greater the curvature of the concave surface, and the net inward pull or pressure will therefore be less the greater the curvature. Similar reasoning will show that a molecule x on a convex surface has a net downward pull or pressure of $(P + p)$ (Fig. 24, *c*).

The *surface tension* is independent of the curvature of

the surface, but the *surface pressure* is dependent on the curvature, because that pressure is determined not only

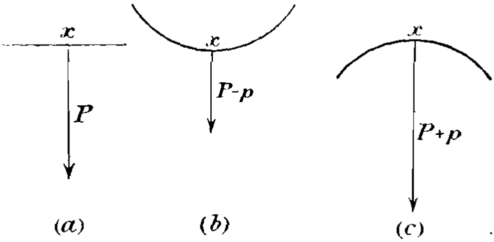

FIG. 24.

by the amount of the surface tension, but also by the directions in which that tension is exerted. The pheno-

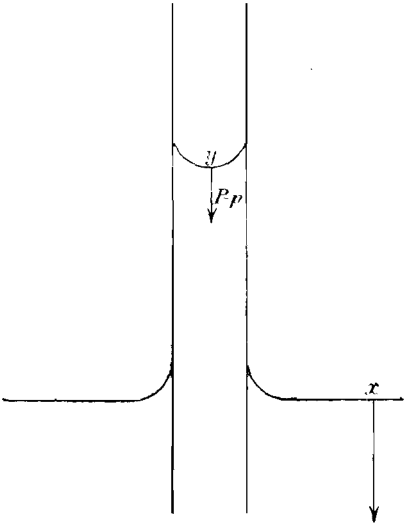

FIG. 25.

menon of *capillarity* is a result of this variation of pressure with curvature of surface. Two common types of capillary movement will be described.

1. If a narrow glass tube is inserted into a vessel of water as in Fig. 25, that part of the water surface which is in the tube becomes concave on account of the greater attraction of the glass for water than of the water molecules for one another. Therefore, as previously explained, the pressure at the point y is less than the pressure at any point x on the level surface. This difference between the pressure on the outside surface and that on the surface inside the tube forces the water up to a height corresponding to the difference of pressure. The narrower the tube, the greater is the curvature of the surface, the lower is the pressure at y and the greater is the height to which the water rises.

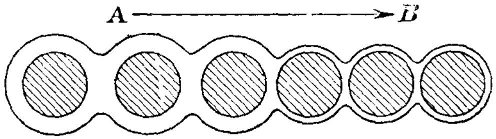

Fig. 26.

2. A second type of capillary movement is illustrated by the consideration of a film of water covering a number of adjacent particles, as in Fig. 26. When the particles are in contact the films coalesce and form concave surfaces between the particles. The greater the amount of water present, the less the concavity. The less the concavity, the greater the pull inwards. Hence water will travel in such a system from a place A where it is more abundant to a place B where it is less abundant, until equilibrium is established.

APPENDIX C

THE REACTION OF AQUEOUS SOLUTIONS

The term *reaction* is applied to solutions in reference to their condition of acidity, neutrality or alkalinity. Acidity is caused in solution by positively charged hydrogen ions represented by the symbol $\overset{+}{H}$ and alkalinity is caused by negatively charged hydroxyl ions represented by the symbol $\overset{-}{OH}$. All aqueous solutions however contain both $\overset{+}{H}$ and $\overset{-}{OH}$. It is the excess of one over the other that causes the solution to be acid or alkaline. Further, not only do all aqueous solutions contain both $\overset{+}{H}$ and $\overset{-}{OH}$ but the number of gm.ions of $\overset{+}{H}$ per litre *multiplied by* the number of gm.ions of $\overset{-}{OH}$ per litre is always constant at a given temperature. At 21° C. the product is $\frac{1}{100000000000000}$ or 10^{-14}. The concentration of any ion in gm.ions per litre is usually written in an abbreviated form by putting brackets round the symbol of the ion. The above statement may therefore be written

$$(\overset{+}{H}) \times (OH) = 10^{-14} \text{ at } 21^\circ \text{ C.}$$

Whatever salts, acids or bases are dissolved in the water or whatever is suspended in the water does not affect this product. If the concentration of the $\overset{+}{H}$ is altered, the concentration of the $\overset{-}{OH}$ alters automatically so that the product is always 10^{-14}, provided the temperature remains unaffected.

Hydrogen-ion Concentration and the Term p_H. Neu-

tral solutions and pure water contain 10^{-7} gm.ion of $\overset{+}{H}$ and 10^{-7} gm.ion of $\overset{-}{OH}$ per litre. Acid solutions contain more than 10^{-7} gm.ion of $\overset{+}{H}$ and less than 10^{-7} gm.ion of $\overset{-}{OH}$ per litre. Thus if $(\overset{+}{H})$ is 10^{-5} then $(\overset{-}{OH})$ will be 10^{-9}, since $10^{-5} \times 10^{-9} = 10^{-14}$. Alkaline solutions contain less than 10^{-7} gm.ion $\overset{+}{H}$ per litre, and more than 10^{-7} gm.ion $\overset{-}{OH}$ per litre. Thus if $(\overset{+}{H})$ is 10^{-10} then $(\overset{-}{OH})$ will be 10^{-4}. For solutions at ordinary temperatures it is not necessary to state both the $(\overset{+}{H})$ and the $(\overset{-}{OH})$ in order to know the reaction of the solution. Either is sufficient and in practice the hydrogen-ion concentration is the one always named. If this is 10^{-7} the solution is neutral. If it is higher than 10^{-7} the solution is acid, if it is less than 10^{-7} the solution is alkaline.

In expressing the hydrogen-ion concentration of a solution it has become customary to adopt an abbreviated form suggested by Sörensen. Instead of writing the concentration as 10^{-x} gm.ion per litre, only the figure x is used. This figure is obviously equal to $-\log. (\overset{+}{H})$. It is generally designated p_H. Thus if a solution has 10^{-4} gm.ion of H per litre, this is expressed by saying "the p_H of the solution $= 4$." If a solution is described as having a $p_H = 10$, this means that it contains 10^{-10} gm.ion of H per litre.

Neutral solutions, therefore, have a $p_H = 7$. The p_H of acid solutions is a number *less* than 7 (since 10^{-6} is greater than 10^{-7}) and an alkaline solution has a p_H number greater than 7.

The Strength of Acids and Bases. In a decinormal solution of hydrochloric acid about 15 per cent. of the molecules of HCl are present as undissociated molecules and 85 per cent. of the molecules are dissociated with the formation of hydrogen ions. In a decinormal solution of acetic acid about 98–99 per cent. of the molecules are present as undissociated molecules and 1–2 per cent. only

are dissociated with the formation of hydrogen ions. Therefore although both the solutions are decinormal, the HCl solution has a very much higher $(\overset{+}{H})$ than the acetic acid solution. Such acids as HCl which are ionized in solution to a large extent so that a high percentage of the replaceable hydrogen is in the form of ions, are called *strong acids*. Such acids as acetic acid which are ionized in solution to a small extent so that a low percentage of the replaceable hydrogen is in the form of ions, are called *weak acids*. Similarly a *strong base* is one which is largely dissociated with the formation of a large percentage of $\overset{-}{OH}$ and a *weak base* is one which is only slightly dissociated with the formation of a small percentage of $\overset{-}{OH}$.

The Measurement of Acidity and Alkalinity. From the foregoing observations it should be clear that there are two totally distinct ways, whose respective results mean totally distinct things, of measuring acidity.

1. *The titration of the acid* measures the total amount of hydrogen which can be substituted by metals in neutral salt formation—the total amount of hydrogen which is ever capable of forming ions.

2. *The determination of the* $(\overset{+}{H})$ measures the amount of hydrogen which is actually present as ion.

In the decinormal solutions of hydrochloric acid and acetic acid there is precisely the same amount of hydrogen per litre which is replaceable by metals in salt formation. Equal volumes of these two solutions will require exactly the same amount of alkali to react completely with them. But the $(\overset{+}{H})$ of the HCl solution is more than sixty times that of the acetic acid solution. The p_H of $\frac{N}{10}$ HCl is about 1 and the p_H of $\frac{N}{10}$ acetic acid is about 2·9.

$(\overset{+}{H})$ and Biological Processes. The student will know that the titration figure is frequently required for

some purely chemical purpose. For most biological purposes, however, it is the $(\overset{+}{H})$ which is required, since the physiological effect of acid or alkali is mainly the effect of hydrogen or hydroxyl ions, and not of the undissociated molecules.

Buffering. Pure water and some solutions are susceptible to considerable changes of $(\overset{+}{H})$ by contact with mere traces of acid or alkali, while some other solutions are much less affected. The reaction of pure water, for example, is considerably influenced by the carbon dioxide of the air, while a solution of sodium acetate is not. Solutions in which the solute tends to prevent changes of $(\overset{+}{H})$ are said to be *buffered.*

A simple and sufficiently accurate explanation of this action is as follows. Acetic acid is a weak acid and is only slightly ionized. Conversely when acetate ions and hydrogen ions come together in the same solution they largely unite to form undissociated acetic acid. While the acid is weak and only slightly ionized, the salts are highly ionized. A solution of sodium acetate contains a high percentage of acetate ions. When, therefore, any influence tends to promote an increase of hydrogen ions the increase is largely counteracted by the acetate ions uniting in undissociated molecules with the hydrogen ions. Silicates, " humates," phosphates, carbonates and the salts of all weak acids exert a buffering action in solution.

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